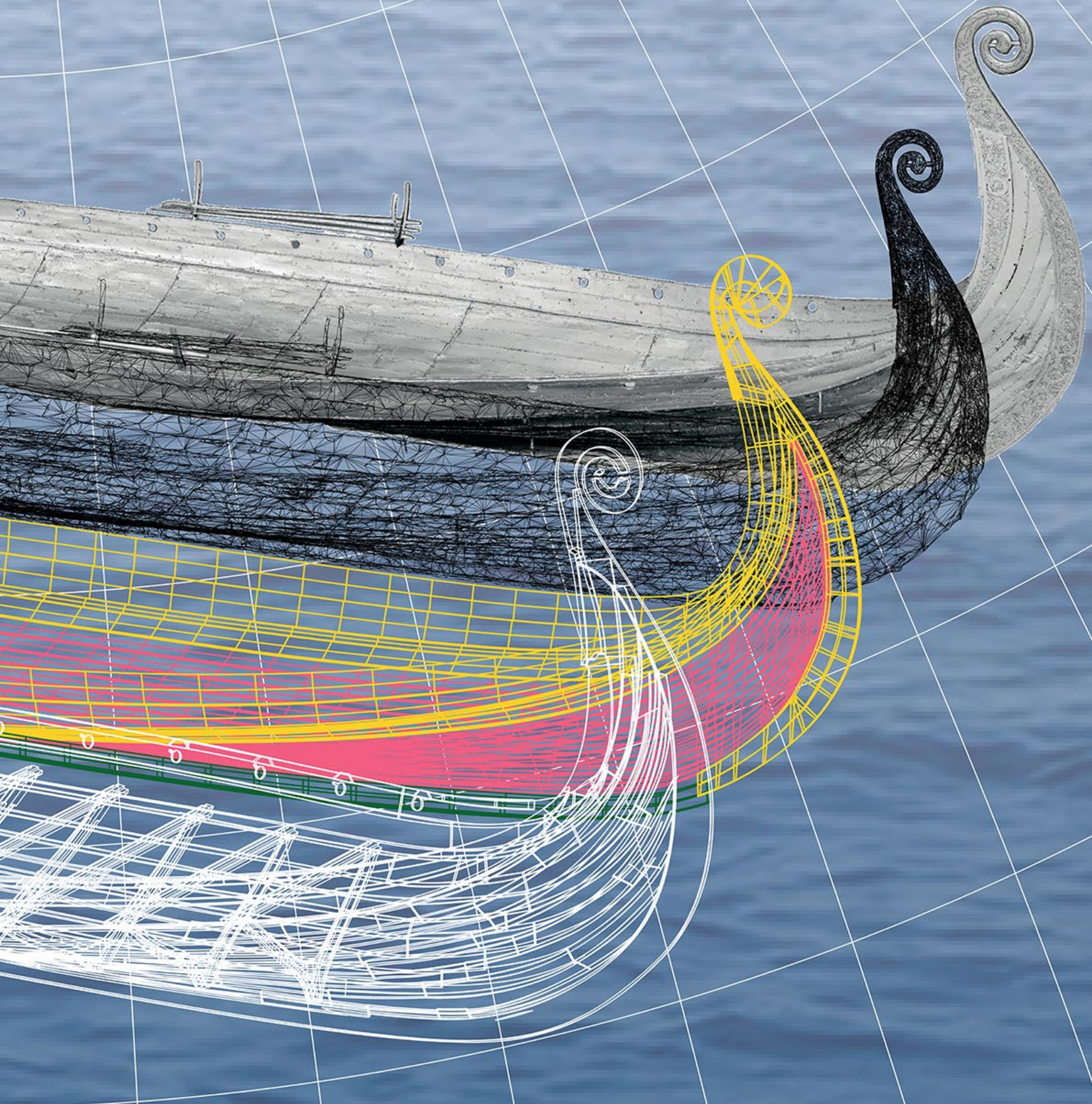
CAA2016

Oceans of Data

Edited by

Mieko Matsumoto and Espen Uleberg



CAA2016
Oslo 30 march-3 april

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Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology

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CAA
Computer Applications & Quantitative Methods in Archaeology

Archaeopress Publishing Ltd
Summertown Pavilion
18-24 Middle Way
Summertown
Oxford OX2 7LG

www.archaeopress.com

ISBN 978 1 78491 730 2
ISBN 978 1 78491 731 9 (e-Pdf)

Language Editing: Rebecca Cannell
Cover Design: Bjarte Einar Aarseth

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Foreword

Archaeological excavation, collection curation, and research are becoming ever more digital. The potential and affordances of this accumulated data are yet to be realised, which is why the 44th conference of Computer Applications and Quantitative Methods in Archaeology — CAA2016 chose the theme *Exploring Oceans of Data*, to denote how important it is to recognise these intrinsic yet up-to-date research questions. The logo, the elegant bow of the Oseberg Viking Ship, reflects the historical role of the city of Oslo, where the brave seafaring Vikings set out to the oceans; their perseverance reminds us of the need to haul digital contents from the vast sea. This theme was well addressed in the opening keynote speech *Oceans of Data* by Christian-Emil Ore.

The main venue for CAA2016 was the University of Oslo downtown campus in the city centre — the assemblage of the oldest university buildings which were completed in 1841–1856. The dominant University Aula, with Greek-style pillars, hosted the opening ceremony, the keynote speech, and the AGM. Presentations were then held here and in lecture rooms located in Domus Media, Domus Academica, Domus Bibliotheca, and Professorboligen (Stallen). Workshops were divided between the campus and the Museum of Cultural History close by. The Frokostkjelleren was the social hub and meeting point throughout the conference.

In all, 360 participants from 37 countries worldwide came together in the early Norwegian spring. The week started with five workshops. Participants were welcomed to the Museum of Cultural History the evening before the conference opening. During the next three days, 26 sessions including two roundtables took place, with 219 papers and 29 posters presented. Social events were organised on two evenings at the Viking Ship Museum and the Oslo Opera House by the fjord. The week ended with two one-day excursions; to Medieval Oslo and Viking Age Vestfold.

This volume contains the 50 highest ranked papers submitted to the CAA2016 Proceedings. They are divided in eight parts including an introduction and seven chapters. The introduction sets the stage with *Oceans of Data* and *Theorising the Digital*, discussing the current status of overall CAA research. The following chapters reflect the themes presented at the conference sessions.

The Museum of Cultural History is proud to have hosted the 44th CAA International Conference, the very first international CAA in Norway. We would like to thank our numerous sponsors: the Norwegian Research Council, the Museum of Archaeology, University of Stavanger; the University Museum, University of Bergen; NTNU University Museum; Tromsø Museum — the University Museum at the Arctic University of Norway; the Norwegian Institute for Cultural Heritage Research; the Norwegian Directorate for Cultural Heritage; the Department of Archaeology, Conservation and History, University of Oslo, and also Archaeopress; Springer; intrasis; Kartverket; Norgeodesi AS; and BETA Analytic Ltd.

We are also grateful to Event Support Services and the Faculty of Law, University of Oslo, who generously let us use their facilities at the downtown campus. The smooth organization was possible thanks to the archaeology student volunteers from the Institute of Archaeology, Conservation Studies and History, the student union at the Faculty of Law, and technical and administrative staff, all at the University of Oslo.

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Introduction

Mieko Matsumoto and Espen Uleberg (eds) 2018. ***CAA2016: Oceans of Data***
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
Oxford: Archaeopress

Oceans of Data: Creating a Safe Haven for Information

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Abstract
The conference theme of CAA2016 was "Exploring Oceans of Data", hinting at the vast amount of digital data resulting from digitisation projects and from all kind of electronic measuring gadgets used to document excavations and surveys. The digital data are much more fragile than paper and can easily evaporate. The last decade we have been told to avoid information islands and the slogan has been "Open the data silos". Is it easier to find a needle in an enormous haystack than in many small? If we are satisfied with the result lists of the google-type answer, it is a clear yes. If we want to build scientific data sets which may be aggregated into larger data sets, we need common authority systems and ontologies for data integration. Archaeology is neither library nor archival science, but methods for construction, curation and reuse of archaeological data sets must be the main focus. Standardised conceptual data models can ease curation and secure long term reusability and will not impose a straitjacket on research.

Keywords: data preservation, reuse, ontologies, linked data

Introduction

The conference theme of CAA2016 was 'Exploring Oceans of Data', hinting at the vast amount of digital data resulting from digitisation projects and from all kind of electronic measuring gadgets used to document excavations and surveys. A quick look at the CAA2016 book of abstracts will tell you that only a minority of the presentations actually address issues connected to curation, organisation and (re)use of the 'oceans' of data. The majority of the presentations are, as at all CAA meetings, about innovative and experimental use of computers in archaeology and about the application of existing technology to new scientific projects, that is, about activities producing even more data.

This is not unexpected. Academic training is in general focused on how to gain new insights. The most important outcome of a project is considered to be the academic publications. Even in empirical fields like archaeology the main path to success is the number and quality of your academic publications. The future faith of the empirical material and the documentation of it accumulated in an archaeological project are of almost no importance after the paper is published. You will not lose your PhD and your paper will not be rejected after having been published in the case of your field material being later destroyed. The system for academic credits gives little or no award for the preparation of your material for long term preservation and even for the development of research infrastructures to keep such material.

The full title of CAA is Computer Applications and Quantitative Methods in Archaeology. In 2012 CAA celebrated its 40th anniversary. The CAA2012 had a special session called "personal histories" where key members shared their CAA memories. The session was captured on video, can be viewed online and is highly recommended (Personal Histories Project, 2012). Most of the memories are about social events and about the primitive state of computers back then, as it should be. However, there were a few caveats, one by John Wilcock who founded The Research Centre for Computer Archaeology at North Staffordshire Polytechnic in 1970 where a number of central British CAA members got their training. With reference to his participation in the rescue work of the data from the very large BBC Domesday Book project (BBC, 2016), originally published on two laser disks in 1986, Wilcock ended his talk with a comment of the importance of proper archiving preferably on paper (!) and stated 'We can't use the Cloud unless we can read it'.

The flood of digital data and the current situation

Wilcock represents the senior league in our field and many may consider his worries as those of the old man. Today almost all new information is born digital and a majority of information in the world is in a digital format. Paper based data are voluminous and less accessible than digital data but are undeniably much more stable and can eventually find its way to collections and archives. Digital data are fragile and will not usually be readable after years in the attic. Without proper actions, the floods of digital data may evaporate and the oceans of data shrink as an Aral Sea. This may not be of importance for a large number of the billions of instant images in the social media. It will however be a catastrophe for our understanding of the past if the carefully collected documentation of all archaeological excavation since the 1990s disappeared. The problem is twofold. The basic challenge is that the digital data must at least be preserved in the format it was recorded. For example old magnetic tapes and home burned CDs tend physically to deteriorate and PCs with hard disks are recycled because nobody remembers or cares what is on them. This seems to be trivial problem, but may be the most widespread reason for the loss of data. To establish a solution to this problem of 'bit-stream preservation' is at the same time very trivial and very complex. It is trivial because one only needs a permanent organisation responsible for taking proper care. It is complex and even very difficult because such a caretaking body will require permanent funding. Even though it is a prerequisite that the digital data are preserved, they may be of little use if we don't know the format and can interpret the data as meaningful information. The second task is to ensure that the data are also stored in an open, transparent and non-proprietary format. Thus a caretaking body must ensure that the data are stored in such a format. This is not always possible. Measurement data from remote sensing equipment like GPR and LiDAR should be stored as raw data with a sufficiently detailed specification of the format to enable decoding of the data. A parallel is the TIFF image format designed so that a skilled programmer can understand the format and decode the data within two weeks-time without any previous knowledge of the format.

To meet the two challenges described in the above paragraph is the basic task for the long term preservation of digital data in all fields — not only for archaeology. In Europe there are two very good examples of institutions taking care of digital archaeological data: DANS in the Netherlands and ADS in UK. In recent years other initiatives have been established, for example the German IANUS (Heinrich and Schäfer, 2016; or Kolbmann, 2014), the US based tDAR (2015) and Open Context (2016) and others. Unfortunately, many countries do not have such services today. In the ARIADNE project the situation in Slovenia and in Ireland has been studied. According to the ARIADNE booklet (ARIADNE, 2014) the situation is far from ideal. From Slovenia it is reported that 'all digital data from excavations prior to 2013 has been left completely in the hands of the researchers, being either public or private legal bodies'. The only open sources are the written short obligatory excavation reports. According to the booklet, there is a growing understanding for the need of a national depository for archaeological data like the DANS, and some initiatives have been taken. In Ireland the situation is quite similar. The economic boom in the 1990s required a large number of rescue excavation done by private contractors. In the following economic crisis after 2008 many of these firms were closed down or went bankrupt. The fate of the digital data from the excavations is at best unclear. In Ireland as in Slovenia the only available information is what is written in the short obligatory excavation reports.

Based on conversations with colleagues it is my impression that the Irish and Slovenian experience is far from unique. In 2015 the Swedish National Heritage Board (Riksantikvarieämbetet) did a survey of the state of the data from contract excavators, both private companies and regional museums (Törnqvist, 2015). The results of the survey describe a picture quite similar to the Irish and Slovenian with some important differences. The data are stored in many different formats on PCs and servers in several formats. Only the reports, mostly printed on paper, are sent to the Swedish National Heritage Board. The contractors report that they don't have the resources to convert, systematise and transfer the data. On the positive side the survey gives a detailed and more or less complete picture and the data are recoverable given sufficient resources. The Swedish National Heritage Board has established a five year programme, Digital Arkeologisk Prosess (Digital Archaeological Process), 2014–2015, where one of the objectives is to take care of the excavation data.

Requirements from the cultural heritage authorities and the availability of organisations like the Dutch DANS ("Digital Archiving and Networking Services") may solve the Irish-Slovenian-Swedish problem which exists in many other countries as well. There are positive initiatives in Slovenia and Austria, but they have to be followed up by modernising the legislation and archiving requirements in the excavators' contracts.

Three levels of data preservation

One may argue that a digital data archive is simply a giant data silo and the stored data are not directly accessible. A silo is a device for safe storage and an important feature is that one can extract in an unspoiled condition what was originally inserted. The availability of safe data silos for long term, say 100 years, preservation of digital excavation data must be the basic requirement, but such services are not available in many, perhaps most, countries. To ensure that excavation data are stored properly for later use is level 1.

Under the assumption that we manage to create and preserve the data sets, how can the data be utilised? In an ideal world it should be possible for a given area to see a map based view of all sites, monuments, excavations and surveys. It should be possible to zoom in and see the excavation area with structures and finds together with a listing of all data sets, reports and publications documenting the excavation and the researchers' interpretations. This will indeed open the silos.

A data set from a given excavation corresponds to a book in a digital library or a box with documents in a traditional archive. It is a closed, self-confined unit. Data archives like the Dutch DANS or the British ADS store such self-confined units. To find the relevant material, users of libraries and archives are depending on a good catalogue with detailed metadata about each archival unit and books. For an excavation archive this will be detailed information about the excavation, for example: where (coordinates), when, how, what was excavated and who was responsible. In addition to being a finding aid in a given archive, the metadata from all archives should be accessible via APIs and as linked (open) data. Combined with site and monument registries this will create a common index to archaeological excavations and surveys. This will not give full access of the content of the data sets, but it will give open access to the storage units in the silos and make it possible to create maps or other aggregated overviews over known archaeological sites and field research as well as information about where to find the data sets. This is level 2.

In the spirit of the open-the-silos slogan, the content of the data sets should be made available as linked data. This is level 3. In this context a photo, a multimedia object or a LIDAR point cloud will be a singleton member of a data set. If it is analysed into smaller parts then the resulting data will be a data set with links to the original.

One may wonder if it is meaningful to combine detailed excavation data from say the Hellenistic Egypt with data from an excavation of an early Iron Age site in central Norway. The degree of meaningfulness of combining data from a series of excavation is, however, up to each researcher to decide. It can be relevant to compare data from sites with long houses from the Merovingian period in North Germany and Scandinavia. On a very local level, say the remains of the medieval town of Oslo, merging the excavation databases into one will indeed be meaningful.

There is always a snag. A meaningful linking of data (and data sets) requires compatible data models. Integrating databases even just on the level of a common index without a common understanding and harmonisation of the semantic categories and the data model is meaningless. Such a harmonisation may require resources well beyond the limited resources of a small single project. Even today most archaeological projects follow the requirements or recommendations in some manual. For example, one will follow the guidelines when taking samples for dendrochronological analysis. Correspondingly, the overall information architecture of an excavation database should follow some well-defined standard model.

Linkable data, linked data and the web

Internet has existed 40 years and World Wide Web was invented for almost 25 years ago. The idea of common access to all archaeological information and research information in general is of course not new. Besides the traditional archives and libraries, an early example is found in Vannavar Bush's 1945 paper, *As we may think* (Bush, 1945). In his paper Bush describes the Memex (Memory Extension), a machine with indexed and interlinked microfilms. The basic idea is that users may add their own association between images on the films, that is, between entries in data sets. These associations or links can also be annotated. Bush argues that this is the way a human thinks. We follow a series of associations, maybe with side tracks. To store such association, links are important, according to Bush. There are clear similarities between Bush's line of arguments and what we can read in papers about hypertext in the 1980s, see for example Conklin (1987) for a time typical overview. It is also worth noting the many web annotation initiatives that follows the suggestions in Bush's paper. A prominent example now adopted by the W3C is the OpenAnnotation Initiative (Open Annotation Collaboration, 2016). The World Wide Web in itself was originally an implementation of the hypertext idea. Curiously it didn't receive much acceptance in the traditionally academic hypertext scholars in the first few years (Richie, 2011). The inventor of the term 'hypertext', Ted Nelson, found the web and html-encoded texts too simplistic compared with his own Xanadu-system. Around 1990 hypertext and text encoding was to a large extent done by especially interested persons in the fringes of departments for language and literary studies. It was definitely not a topic of great interest among archaeologists. One of the few exceptions must have been the late archaeologist Sebastian Rahtz who later was active in the TEI-community (TEI, 2015). The first very few CAA discussing hypertext and linking of excavation archives was given by the late Nick Ryan at CAA1994, *The Excavation Archive as Hyperdocument?* (Ryan, 1995). The year after, the first paper on extraction of information from XML-encoded archaeological texts was presented at CAA1995 (Holmen and Uleberg, 1996). At CAA1997 the elegant Danish initiative *Gods and Graves* (Hansen, 1999) was presented. This was a web publication combining the Danish sites and monuments registry and the finds database at the Danish National Museum.

Since then web presentations of archaeological information has become the normal. Web based services for archaeologists followed suit. At CAA1996 *ArchWeb* (Wansleeben and van den Dries, 2000) was presented. This was a web based data service for archaeologists in the Netherlands. ArchWEB was a forerunner for the very successful *E-depot Dutch archaeology* (EDNA) at DANS which was launched ten years later, in 2006. As mentioned earlier, a general problem is that in most countries there are no formal obligations to deposit digital excavation data in a common permanent archival system. In many countries (e.g. Ireland, Norway, Slovenia, Sweden) the only requirement is to send a short excavation report to the archaeological authority. The success of DANS is founded on the obligations to deposit the data and the existence of an easy to use deposit system with a formal quality standard the (meta) data must conform to.

Both DANS in the Netherlands and ADS in UK have become successful archives for archaeological data sets. Well-functioning data archives are an absolutely necessary condition for access to data sets. The existence of the data sets is in itself not a sufficient condition for exchange or aggregating data in a meaningful way. The issue has been discussed in many CAA presentations starting with Nick Ryan in 1994 (Ryan, 1995), see also Verhagen, Sueur and Wansleeben (2011) for a practical discussion.

The need of well-defined common conceptual models

In 2001 Berners-Lee, Hendler and Lassila (2001) foresaw a second web, the semantic web, readable for computers and based the RDF-technology. Compared with the traditional web it has not become an undisputable success. Five years later Berners-Lee (2009) suggested a more concrete and practical solution called Linked (Open) Data:

- Use URIs to identify things.
- Use HTTP URIs so that these things can be referred to and looked up by people and user agents.
- Provide useful information about the thing when its URI is dereferenced, using standard formats such as RDF/XML.
- Include links to other, related URIs in the exposed data to improve discovery of other related information on the Web.

The linked data mechanism has become very popular, for example in DBpedia. It is easy to understand, implement and use. In a CAA context especially spatial referential data and type thesauri, are published as Linked Open Data (LOD). In many linked data communities the focus has been on making as much data available as possible under a somewhat post processual device 'everything can be linked':

- Increased amount of data = Increase of amount of information
- Increased interlinking = Increase in information
- Popular view: everything is connected to everything

This is of course not true and may be called 'the principle of entropy fallacy'. Information is generated through exclusion using meaningful distinctions according to a common conceptual model or formal ontology. Organising data using such ontologies and the ontologies themselves can be expressed as RDF triples. Consequentially, Linked Data can function as a medium for generating meaningful statements about data. In other words, to create more than trivial use of linked data in a domain, the linking has to be in compliance with a well-defined ontology for the domain in question.

In Finland a series LOD projects called 'sampos' (after the Finnish mythological object sampo) for Finnish history and culture has been published. The team behind many of these lead by Eero Hyvönen at the Aalto University argues that the well-known 5-star (Bernards-Lee, 2009) model for Linked Open Data should be extended to a 7 star model. The sixth star requires that the schemas (RDFS) used in a LOD data set are explicitly described and published together with the data set if not publicly accessible on the web. The seventh star requires that the "quality of the data set against the given schemas used in it explicated so that the user can evaluate whether the data quality matches her needs" (Hyvönen *et al*., 2014). The most recent of these sampos, called the WarSampo, is about Finland in the Second World War and links a large number of data sets. In WarSampo CIDOC-CRM (CIDOC CRM, 2016.) is used as the harmonising basis for modelling data, with events providing the semantic glue for data linking (Hyvönen *et al*., 2016). This is an elegant example of an advanced LOD application scalable through the use of a common conceptual model designed for data integration. According to Hyvönen the Finnish WarSampo can be extended to larger parts of the history of Second World War by mapping the content of archives and collection to the common conceptual model. There is some distance from the Finnish WarSampo to archaeological excavation data sets. Still the WarSampo illustrates what can be achieved.

Even though an excavation plan may change due to unexpected finds, the documentation methods will usually remain constant. The recorded information will be the result of human interpretation. Raw data are not raw (see Gitelman, 2013). They are a result of both the excavation plan and method and an

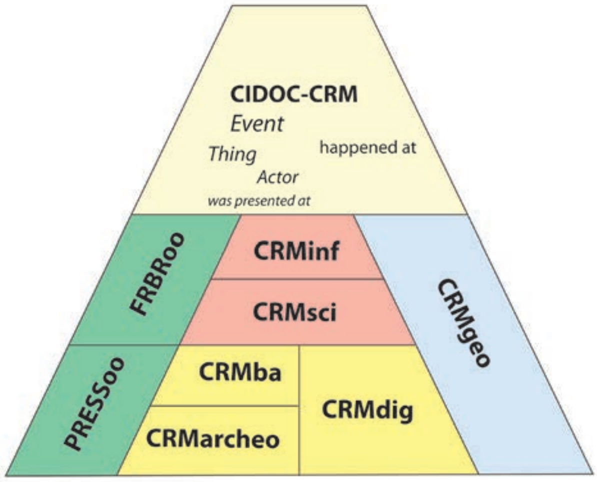

Figure 1. The CIDOC-CRM family of models.

interpretation of what is observed. The sixth and the seventh stars have to be a part of the excavation data set. A data set from an excavation without an explicit data model is meaningless. It is like artefacts without contextual information. To achieve something like an 'ArcheoSampo', the data sets have to be mapped to a common ontology. The original data sets must be kept and the mapping must be formally described. The ARIADNE project is an excellent example of how this can be done by using the family of the CIDOC-CRM ontologies and the mapping specification language X3ML (Marketakis *et al.*, 2016).

A comment on the situation in Norway

In Norway the situation is easier with fewer actors. As a result of two large digitisation and database projects 1992–2006 (see Holmen and Uleberg, 1996; Ore, 1998) there is one common database for finds and one for the site and monuments registry. The overarching data model was inspired by the event oriented model developed at the Danish National museum in 1988-89 (Eaglestone *et al.*, 1996; Rold, 1993), and the data format for texts was based on TEI (Text Encoding Initiative) (TEI, 2015) developed by text philologists from 1987 onwards.

In Norway excavations are done by 7 museums, 19 counties and one semi private foundation. The Swedish GIS based documentation system INTRASIS (see Intrasis, 2016.) for archaeological excavations has become a de facto standard. Even in this tidy situation the backlog of digital excavation data from 1990 and onwards is also a problem in Norway. There is no common database with data sets from excavations and the archival praxis is varying. The Norwegian archaeological institutions must dare to take the small step to publish their data sets in the similar way as is done by DANS and suggested by the ARIADNE project.

Summing up

Archaeology is neither library nor archival science. But a substantial part of archaeological training is how to do sound and accurate documentation of contexts. Methods for construction, curation and reuse of archaeological data sets should be in the central focus as well. Standardised conceptual data models can ease curation and secure long term reusability. Used for these purposes models will not put straitjackets on research.

In the 1980's the hypertext was thought to do the job. The web in the 1990's was an implementation of hypertext on a global scale. Linked data and the semantic web followed without really solving the problem.

The last decade we have been told to avoid information islands and the slogan has been 'Open the data silos'. Is it easier to find a needle in an enormous haystack than in many small? If we are satisfied with the result lists of the google-type answer, the answer is a clear yes. If we want to build scientific data sets which may be aggregated into larger data sets, we need common authority systems and we need to impose some common structure on the data. To do this in a meaningful way, we have to do an ontological analysis of why and how data are produced in our disciplines. That is, we need to understand our data and establish consistent and well-founded data models or ontologies, (Oldman *et al.*, 2016). On the basis of those we can see how our data may be mapped to a common model for integration. Well defined data models are necessary to define standards for storage formats and may help us to write the necessary specification for contract excavators.

In the CAA context the main focus will and should be on innovative ICT applications and good practice. The methodology of common consistent but flexible models for data integration will be a relatively small, but important core activity. The data and the artefacts is all what remains from an excavation. They must be handled with care. We need to create accept among the stakeholders that data are at least as important as the artefacts and need long term curation. This is a task for the entire CAA community as well as for the cultural heritage sector as a whole.

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Mieko Matsumoto and Espen Uleberg (eds) 2018. ***CAA2016: Oceans of Data***
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Theorising the Digital: A Call to Action for the Archaeological Community

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Abstract

Although archaeologists are increasingly critically engaged in their deployment of computational approaches, those who label themselves as 'digital archaeologists' are typically not recognised for their philosophical contributions to the discipline and are rarely positioned at the forefront of general disciplinary theorising. Indeed, where digital archaeology does feature in volumes on archaeological theory, it often amounts to little more than a footnote. This is in spite of the fact that digital archaeologists have been driving change in archaeology for more than a half-century now. Notwithstanding the support of major international organisations and widespread commitment to key social projects (e.g. open access, 'slowness', neoliberal critique, emancipation), digital archaeologists still do not seem to have the rubrics in place to force larger theoretical shifts in the discipline. We aim here, then, to begin identifying the gaps and tensions which hamper our capacities to write contemporary and future archaeological theory.

Keywords: digital archaeology, theory, practice, critique, reflexivity

Introduction: gaps in (digital) archaeological theory and method

'We are all digital archaeologists' is an increasingly common refrain amongst practitioners today (e.g. Morgan and Eve, 2012, p. 523). However, the ubiquity of computational approaches in archaeology still seems little understood. Debates about the philosophical or cultural dimensions of digital technologies in the discipline have a deep legacy, yet the technical capacities of these tools still tend to eclipse meaningful critique of their implications. Problematically, it is usually the applications of computers that become the overwhelming focus of digital archaeological discussions at our conferences, in our written work, and often in our classrooms too.

This trend to value the technical above the theoretical is one that is seen across many fields (see below) — and it is made worse by the fact that it tends to betray itself again and again as any new piece of equipment is added to disciplinary toolkits. The *Computing Applications and Quantitative Methods in Archaeology* (CAA) enterprise itself hints at the predicament, for applied methodology is foregrounded in the organisation's very name, with richer qualitative analyses of the digital seemingly consigned to the backstage.

However, closer interrogation of the history and present of digital practice in archaeology suggests a wealth of critically — engaged and theoretically — progressive work in the discipline. Digital archaeologists have been driving methodological change in archaeology for more than a half-century now. As discussed below, today they can also be found at the vanguard of critical social action — from open access and 'slow' movements, to public engagement initiatives and neoliberal critiques. Yet they are rarely, if ever, cited as meaningful players in disciplinary philosophising, nor do they have any real visibility in our key archaeological theory texts.

As we see it, digital archaeologists (us included) are guilty of not explicitly positioning themselves at the heart of the larger discipline. And while we ostensibly have the power to drive forward general archaeological theory, we still seem not to have the rubrics in place to impact these larger conceptual shifts. We aim here, then, to begin identifying the gaps and tensions which hamper our capacities to write contemporary and future archaeological theory. These tensions include everything from digital archaeology's humble modes of disseminating academic papers (e.g. in obscure conference proceedings), to the CAA's seeming lack of voice in interdisciplinary affairs. Where, for instance, is the CAA's code of ethics?[1] Where are its press releases in response to matters of wide public concern (as done in all major archaeological organisations, from the World Archaeological Congress to the European Association of Archaeologists)?

Costis Dallas (2015, p. 177) has outlined the problem as such: 'questions of huge impact to archaeological theory

[1] Note that this paper was delivered in March 2016, and in March 2018 a code of ethics has indeed been published by the CAA. One of the authors (Perry) has been involved in its preparation.

and practice during the last half century, stemming from post-colonial, feminist, indigenous, Marxist, and hermeneutic approaches, appear to be peripheral in the literature, subject-matter, and interests of digital archaeology.' While we would contend that these questions of impact are increasingly shaping digital archaeologists' work, we build on the arguments of Dallas and others to suggest that the predicament is born out of — and exacerbated by — the lack of a larger critical disciplinary framework to guide digital practice. Without such a critical framework in place, the whole field of archaeology suffers.

To make our case, we begin by looking in depth at Geographic Information Systems (GIS) and their integration into both archaeology and geography. Our interest in the latter discipline stems from the fact that it too has wrestled with comparable issues, hence offering us an opportunity to learn from previous experience. As we hint, where things appear to destabilise is at those moments when new technologies are added into disciplinary practice. Arguably, in archaeology, this destabilisation results from the fact that such technologies are being introduced into a system that does not, in most cases, *purposefully* and *always* (or ever) force critical attention onto their socio-technical dimensions. We go on to review current critical theory in digital archaeology to assert that we already have the infrastructure in place to design and roll-out a discipline-wide, purposeful reflexive theory for the digital age in archaeology. We conclude, then, by arguing that our challenge is to realise this reflexive, computationally–informed framework, and hence put digital archaeologists at the centre of theorising in the discipline, rather than systematically and continuously relegated to the side-lines.

The rise and peak of GIS, and the emergence of critical GIS

By way of illustration, it is useful to consider the relationship between archaeology/archaeologists and one of the discipline's oldest (ca 50 years old) and more widely accepted and applied digital technologies, Geographic Information Systems (GIS). The following section seeks to link the general development of geospatial technology hardware and software to their application across the archaeological discipline. Our intent is to connect these technologies to broader trends in the history of cross–disciplinary critical thinking about computing technology, thereby testifying to the long genealogy of such work.

The first GIS implemented by the Canadian government's Regional Planning Information Systems Division in 1964 was initially developed as a tool for the large-scale management of landscapes and environmental, cultural and political resources (Wheatley and Gillings, 2002, p. 13), but was quickly adopted elsewhere in North America and beyond. As a system combining cartography, image processing, data management and analysis within a spatial framework, the development of GIS in the subsequent decades was generally pioneered by universities and government agencies, with a specific top-down agenda which has been linked to post-war trends in urban and rural planning and redevelopment (*ibid.*). This process of development, and the subsequent uptake of these Spatial Technologies (ST) by the commercial sector, has been well documented and discussed elsewhere (e.g. Pickles, 1995a; Peuquet, 2002; Wheatley and Gillings, 2002, pp. 13–22; Conolly and Lake, 2006, pp. 1–32; and see also Lock, 2003 for an introduction to the way in which the technology was adopted by the archaeological discipline).

What is particularly interesting to us is how GIS rapidly became adopted by, and made the main analytical tool of, the broader discipline of geography. The way in which this happened within geography's academic sphere, and the resultant critique, is a useful analogy for archaeology's own relationship not just with GIS, but with technology more broadly. Crucially, up until the mid-90s (i.e. for close to 30 years after its initial invention), GIS was primarily deployed as a technical tool. It has only been in the last 20 years or so that deeper consideration of the social, political and ethical implications of its application has emerged, primarily as a result of wider postmodern critique.

Generally, there have been three waves of emergent critique of GIS and related technologies within the sphere of geography rooted in this postmodern standpoint (O'Sullivan, 2006). The *first wave*, emerging in about 1995, focused upon critiquing the social history and positivist roots of the technology, highlighting its quantitative focus (Pickles, 1995a; Sheppard, 1995; Kwan, 2002a). It called into question the 'top-down' hierarchy and power dynamics of GIS technologies — arguing that these technologies were *exclusive* (i.e. technologically elite, in that they required a large amount of expertise to operate and use effectively), *undemocratic* (having been developed initially as military or governmental applications, and later by large software companies), and ultimately *disempowering* for many users (for the above reasons) (Pickles, 1995b).

After a decade of critical engagement with these sorts of issues, a *second wave* of critique of GIS and STs began to emerge (Schuurman, 2000). (Note, too, the parallel of these critiques, both in timing and in substance, with the emergence of the post-processual school in archaeology — also rooted in a disciplinary — level postmodern critique.) Solutions or challenges to the characterisations offered by the first wave began to be offered that called for GIS to incorporate non-cartographic (qualitative) spatial knowledge in order that it might be used as a progressive research tool to explore wider themes in critical human geography, such as 'environmental justice, gender, class and race analysis' (Marianna Pavlovskaya *in* Wilson and Poore, 2009, p. 8). Notably, a specifically feminist GIS was then born, rooted in the analytical needs of an emerging feminist geography. Simply put, feminist GIS sought both to call into question the connection between GIS and broader masculinist (positivist) epistemology, and to examine the potential of GIS and STs to help represent, understand and analyse the implications of gendered spaces and agency within those spaces (see for example Kwan, 2002a, 2002b; Pavlovskaya, 2006; and for an excellent case study, see Kwan, 2008). Closely related to this was the emergence of a qualitative GIS that promoted mixed methods in geographical research, with a focus upon qualitative spatial data, in turn questioning the traditional constraint of GIS technology as a predominantly quantitative (read: positivist) tool (see Kwan and Ding, 2008).

More recently, this last strand of Critical GIS (as it has become known) has developed and evolved again, as part of a third wave of critique. In an effort to directly address issues of empowerment and to democratise the process of knowledge production, another sub-discipline has emerged known as Participatory GIS (see Pavlovskaya, 2002; Elwood, 2006). This disciplinary trend advocates 'bottom-up', community-based GIS practice, which seeks to encourage positive social change from production of geographic knowledge at the community level. Recently this type of participatory practice has begun to structure a form of 'Neo-Geography'; the agenda of which aligns with recent academic concern for the concept of "big data" and local political interests (e.g. the UK's "Big Society" and "Local Voice").

Ultimately, these emerging Critical GIS practitioners, in their respective waves, began to ask (and try to answer) conceptual and epistemological questions about GIS and the way in which it helps produce knowledge. Together, these key components and the associated theoretical discourses have led to the evolution of a broader disciplinary bubble within geography, known now as Geographical Information Science (GIScience). It, in turn, has resulted in some very interesting, 'left–field', theoretically — engaged and intellectually — challenging applications of GIS (see for example Hannah, 2008; Kurban *et al.*, 2008; Kwan, 2008; Wilson, 2009; Zook *et al.*, 2010; Elwood and Mitchell, 2012).

As GIS took root in geography, so archaeology began to explore its potential for solving discipline-specific spatial problems. By the mid-1990s, experimentation with GIS, particularly at the landscape level, had become quite common in archaeology, and was increasingly exposed to the growing ideas of the emerging post-processual movement. In its own way archaeology began to theorise its use of GIS (see for example, although not exclusively Zubrow, 1994; Barceló and Pallarés, 1996; Llobera, 1996; Gillings, 1996; Voorrips, 1996; Barceló and Pallarés, 1998).

However, whilst explicitly acknowledging its post-processual agenda and, to some extent (from a spatial perspective), the important critiques of postmodern geographers such as David Harvey and Edward Soja, it is important to note that this corpus of literature (and subsequent scholarship) rarely cites the critical GIS literature outlined above (although see occasional notable exceptions like Hacıgüzeller, 2012, or Dunn, 2017). This is in spite of explicit recognition by many GIS practitioners within archaeology of the technology's 'theory-laden-ness' (Hacigüzeller, *ibid*, p. 246). Moreover, there has been no equivalent *systematic* critique of the application of geospatial technologies within our own discipline. McCoy and Ladefoged (2009, p. 282) neatly summarise this fact, pointing out that:

> 'for many years the relationship between spatial technology and archaeology has been likened to the "law of the hammer" (Moore and Keene, 1983) in that the appeal of the technology has caused excessive, gratuitous application, or pounding, without regard to purpose, appropriateness, or theory' (Drennan, 2001, p. 668).

However, they do go on to argue that the balance is gradually being redressed, highlighting a number of key factors including: links to strong theoretical developments in landscape archaeology, which aims to use ST to solve archaeological problems, rather than being led by the data; trends at a disciplinary level towards teaching ST practitioners the fundamental principles that drive the technology; and increasing technological 'savviness' pertaining to the 'strengths and limitations' of these technologies (McCoy and Ladefoged, 2009, p. 282; see also Evans and Daly, 2006, p. 3).

More recently, Mark Gillings has painted a rather bleak picture of the relationship between GIS and wider theoretical discourse, highlighting what he perceives to be a dysfunctional, even irreparable schism between GIS practitioners and landscape theorists (Gillings, 2012, pp. 601–602). Not everyone would take such a dim view of the situation or agree that it is right to 'give up' on a wider cross–discipline theoretical dialectic, but ultimately it might be argued that Gillings' end goal is the same as ours: a call for a more critically–engaged, theoretically–driven application of technological methods within the discipline.

Beyond GIS — the digital turn in archaeology

Of course, the 'digital turn' in archaeology extends far beyond the application of GIS and STs, and includes a whole range of quantitative and qualitative methods, statistical approaches, and applied computational technologies, linked both to the development of software and hardware, and to larger cultural trends towards sharing, collaboration, openness, and interconnectivity. However, as we see it, critical attention to the intellectual, political and economic impacts of these digital applications is still overshadowed by results-driven, technically–oriented work. Indeed, from our perspective, digital archaeology might in some cases be mistaken for a form of 'neo-processualism', focused on specifications, accuracy, and precision as means to generate increasingly 'real' archaeological models. Indeed, the content of related scholarship often falls into a cliché that proclaims time and again: 'Look at the size of my point cloud!'

In a piece written for the peer-reviewed blog 'Then Dig' in 2013, Stuart Eve reflects upon his research interests in 'mixed augmented reality' (at the time a 'bleeding edge' technology in its own right) in archaeology and the heritage sector. In it he refers to the 'Gartner Hype Cycle for Emerging Technologies,'[2] which illustrates how technologies are adapted over time. The cycle builds upon the idea that, after its 'technological trigger', emergent technology moves through a *hype* — 'peak of inflated expectations' — into a 'trough of disillusionment' ('having been overhyped…it gets knocked for being overhyped'). Then, with the hype dying down, the technology matures through a 'slope of enlightenment' to a 'plateau of productivity', as the potential of the technology is explored and applied to real-world problems (Eve, 2013).

Indeed, many technologies which might typically be seen as new or emergent actually have relatively long developmental histories. 3D technologies are no exception here. In terms of excavation practice, for example, many major projects have adopted them in recent years as means of primary data acquisition and recording in the field (see for example Doneus and Neubauer, 2005; Callieri *et al.*, 2011; Dellepiane *et al.*, 2012; Forte *et al.*, 2012; De Reu *et al.*, 2013; Dell'Unto, 2014; Forte, 2014; Opitz, 2015; Berggren *et al.*, 2015; Forte *et al.*, 2015; Opitz and Limp, 2015). The origins of 3D technologies, however, such as structure from motion and laser scanning, can be traced back 50 years in some cases.[3] Yet most of these technologies have not really been freely available (i.e. affordable and useable) in a practical sense at a disciplinary level for more than 5 or 6 years. Compare that with the 30+ years of development, critique and theoretical engagement with GIS, which has been accessible to researchers for a much longer timespan, and has resulted in the sub-discipline of GIScience, and it might be argued that 3D technologies do, in fact, have a long way to go. However, that some of these so-called 'new' technologies are actually fairly mature suggests that time passed may not make much difference to the development of a critically self-aware approach in their deployment. Crafting a broader critical framework in which these methods can be embedded *as they are adopted* may be better means to circumvent the effects of the hype cycle.

Having said this, as noted already, it would be wrong to suggest that archaeologists never theorise their digital methods. Indeed, on the contrary, there is a long history of theoretically-grounded critique, evaluation and data synthesis amongst digital practitioners. Early on this was typified by stand-alone articles (again, with specific reference to GIS, see for example Barceló and Pallarés, 1996; Llobera, 1996), or papers delivered within the framework of the CAA (see for example Lock, 1995; Wheatley, 1993, 2000; Wise, 2000). However, it took time for a coherent corpus of theoretical digital papers to emerge, and these standalone efforts often seem not to have been presented outside of the CAA to the wider discipline.

Later, a body of theoretical literature began to coalesce, as the wider implications of the digital turn became more obvious at a disciplinary level. These are typified, for example, by Lock and Brown's (2000) volume *On the Theory and Practice in Archaeological Computing*, derived from a 1999 WAC session; and by Evans and Daly's (2006) volume *Digital Archaeology: Bridging Method and Theory*, born out of an earlier TAG session in 2000 entitled "Archaeological Theory for a Digital Past". A scan of this latter volume reveals papers ranging across a wide variety of theoretical issues including, for example, historiographical review of digital archaeology; consideration of the way increasing 'mountains of digital data' are archived without a clear understanding of their end purpose (strangely prescient of the 'Oceans of Data' theme of the CAA 2016 conference); synthesis of higher order theoretical concepts of gender and identity from statistical analysis; modelling and analysis of real world processes to explore the interaction of humans and their environment; landscape visualisation and critical consideration of issues of scale (the latter being

[2] http://www.gartner.com/technology/research/hype-cycles/

[3] Structure from motion is related to a longstanding tradition of photogrammetry in archaeology, with the earliest attempts to recover a 3D scene from stereo images taking place in the mid-late 1970s (see Marr and Poggio, 1976; Ullman, 1979). Similarly, laser scanning technology is also a relatively old technology, with the earliest scanners being constructed in the 1960s and available in industry since the 1990s.

a theme that is taken up again, often from a digital perspective, in Lock and Molyneaux's subsequent 2006 edited volume); the impact of 3D visualisation on the understanding of archaeology; and means for disseminating digital information (Evans and Daly, 2006).

Our point is that critically and theoretically-engaged discussion of the digital turn already exists within archaeology: it has always been there, but it tends to get lost in wider discussions of the technicalities or presentation of results. As we see it, this predicament stems from the fact that there is not yet a framework (akin to what we have seen developed in geography) within which these sorts of discussions can take place — that is, there is not yet a critical — and critically reflexive — digital archaeology.[4]

Reflexive theory for archaeology in the digital age

So, despite its relatively *ad hoc* development within the discipline of archaeology, there is an obvious genealogy of critical reflection on digital applications in archaeology. Indeed, in the past year alone (2015–2016),[5] a substantial number of new academic outputs on this subject matter have been published, reinforcing the long history of critical digital practice (e.g. Caraher, 2015; Dallas, 2015, 2016; González-Tennant, 2015, 2016; Huggett, 2015a, 2015b; Jeffrey, 2015; Kansa, 2015; Perry and Beale, 2015; Reilly, 2015; Watterson, 2015; Alcock *et al*., 2016; Cooper and Green, 2016; González-Tennant and González-Tennant, 2016; Opitz and Johnson, 2016; Taylor and Gibson, 2016). These publications variously attend to digital visualisation, gaming, interface design, 'big data', 3D printing, virtual worlds, online teaching and learning, social media (including crowdsourcing and crowdfunding), and more. Yet, by our interpretation, most converge on a comparable set of conceptual concerns, suggesting that a reflexive theory for archaeology in the digital age is already in the making. As we discuss below, the robustness and coherence of this emerging theory can be debated — indeed, with a handful of exceptions, it seems relatively rare for its authors to cite from one another, and there are worrisome trends towards bias in existing citation practice. However, the foundations for a critical digital archaeology are being laid, and by our reckoning, digital practitioners now have a responsibility to recognise and actively shape their proportions. In so doing, we suggest that a framework can be mapped out to ensure future technological developments in the discipline are always and necessarily subjected to consideration of their socio-politico-economic dimensions.

While we do not have the space here to review all recent digital archaeology publications in depth, we argue that a not insignificant number of them make a similar case (whether implicitly or explicitly, although usually by way of example) for a more complex, considered and creative form of practice. Namely, they call for (digital) archaeologists to design systems and infrastructure that enable — or literally force — forms of criticality. These might include:

- Developing workflows that purposefully foster slowness or time for reflexivity and introspection (e.g. see Caraher, 2015; Huggett, 2015a; Kansa, 2015; Opitz and Johnson, 2016).
- Crafting systems that embrace complexity (rather than systems that work to standardise), valuing data's specificity rather than trying to wash over specifics in the hopes of generalising. To borrow from Cooper and Green (2016, p. 294), the aim here is to protect the 'characterful' nature of digital data.
- Studying the derivation of data and information systems themselves, their temporal and relational qualities, their histories of production and circulation (e.g. Cooper and Green, 2016).
- Reconfiguring our graphical user interfaces (and general modes of publication) in order to reframe the research process and engender theoretical debate through novel forms of engagement (e.g. Opitz and Johnson, 2016; Copplestone, in prep).
- Rewriting our codes of conduct and ethics to better align with the digital age and to account for the complexities of human and non-human interaction with digital media and digital worlds (e.g. Dennis, in prep).
- Prioritising and designing reward systems for creativity or seeking to foster the creation of unusual, inspiring, innovative outputs that go beyond mere data capture/replication (e.g. Watterson, 2014, 2015; Jeffrey, 2015; Reilly, 2015).
- Using coproduction and forms of public engagement to, as Jeffrey (2015) puts it, mitigate the 'weirdness' of the digital object; to draw attention to the craft, labour, aura, use, reuse and other potentials (and problems) of these media.
- And, more generally, developing models of practice that draw explicit attention to the moral, aesthetic, political and structural implications of the data and their architecture (e.g. González-Tennant, 2015; González-Tennant and González-Tennant, 2016).

Some of the most innovative recent digital archaeology projects — by practitioners like Eve (2012), Hacıgüzeller

[4] We do not have the space here to explore the history, varying definitions and critiques of critical archaeology and reflexive archaeology, but we take as our basic starting points Hodder (1997) and Leone *et al.* (1987). A handful of recent engagements with archaeological theory (e.g. González-Ruibal, 2012; Kristiansen, 2014; Thomas, 2015) are also discussed below.

[5] We have focused on 2015-2016 merely to highlight the weight of recent published work on the subject matter.

(2012), Morgan (2012), Tringham and Stevanović (2012), Watterson (2014, 2015), González-Tennant (2015), Jeffrey (2015), Reinhard (2015, 2018), Opitz and Johnson (2016), González-Tennant and González-Tennant (2016), Tringham (2017), Copplestone (in prep) and Dennis (in prep) — are centred on creating digital interventions that not only advance archaeological research and method, but that focus us on thinking differently about what archaeology is and what it could be in the future. In many cases, these archaeologists are both purposefully deploying varied forms of sensory engagement (smell, sound, touch, etc.) and literally opening up our archaeological landscape (to include virtual worlds, contemporary artefacts and media), using the digital as subject and object of research — as tool to think with and means to critique.

Although typically unacknowledged by archaeologists (but see Huggett, 2015b), such proposals follow broader trends in the digital humanities and social sciences wherein practitioners seek to push back against the obfuscating tendencies of digital culture. As Posner (2015; also see Marar, 2015 among many others) puts it, 'many of the qualities of computer interfaces that we've prized, things like transparency, seamlessness, and flow, privilege ease of use ahead of any kind of critical engagement (even, perhaps, struggle) with the material at hand.' By Posner's reckoning, current digital applications generally make it near-impossible to recognise or interrogate power dynamics at play, leaving us blind to (and liable to reproduce) structural inequalities (e.g. see Bernbeck, 2008). In contrast, the best and most promising of contemporary digital culture is daring, difficult, unorthodox — it entails projects which 'scrutinize data, rip it apart, rebuild it, reimagine it, and perhaps build something entirely different and weirder and more ambitious' (Posner, 2015). Carrigan (2016) calls this the 'challenge of reflexivity', and we would suggest that many of the digital archaeological practitioners cited above are already confronting this challenge, using similar language to define it, and working to construct new systems to determinedly cultivate reflexive digital engagements.

In fact, one might suggest that such digital archaeologists are actually already operating at a more progressive level than other theoretically-inclined practitioners in the discipline. A variety of criticisms have been launched at the latter, particularly those focused upon so-called community-based and collaborative archaeology. As González-Ruibal (2012, p. 157) puts it, their 'emphasis on soft multiculturalism, ideas of consensus, individualism and multivocality (all in tune with neoliberalism)' has done little more than 'depoliticize the discipline rather than the opposite'. Conversely, a not-insignificant cohort of the digital archaeological community has been *explicitly political* (e.g. see the work of Morgan, 2012; Richardson, 2014; González-Tennant, 2015, 2016; Kansa, 2015; González-Tennant and González-Tennant, 2016; Taylor and Gibson, 2016), working to achieve precisely what González-Ruibal (2012) identifies as a crux of critical archaeology in general, namely a commitment to 'expose the darkest side of modernity and, particularly, capitalism' (p. 157) — 'to take sides with the options that challenge hegemonic power...to support those narratives and actions that represent freedom and equality' (p. 158). Borrowing from Bernbeck (2008, p. 395), 'one of the first tasks of a truly 'reflexive archaeology' is to investigate the ways in which the discipline is complicit in legitimizing structures of stark inequality.' Many of the practitioners cited above are doing just that.

Accordingly, given the traction for a critical, reflexive (digital) archaeology, we are left to wonder why digital archaeologists are so often (or always) written out of contemporary archaeological theory. Why are they regularly perceived as atheoretical? Why is there so little recognition of the growing amount of ambitious digital work that has the capacity to reframe the general archaeological workflow, not to mention the very foundations of archaeology's philosophies? We, too, as authors of this paper and co-hosts of the first 'digiTAG' (Digital Theoretical Archaeology Group) event at the CAA conference in 2016 (from which our argument is born) are guilty of throwing out the accusation that digital archaeologists often lack a critical eye. We ask, then, what is at work here in fostering such misunderstandings? And what are the consequences of ignoring the predicament?

Challenges to writing a reflexive (digital) archaeological theory

The discipline sits today at an interesting theoretical crossroads, with scholars at variance about the coherence and dimensions of current trends in archaeological thought (cf. Kristiansen, 2014 with comments; Thomas, 2015). Where digital engagements enter into these debates, they are generally attended to in the most naive of ways — focused primarily on the *promise* of "big data" and social web/online public communication for reconfiguring our thinking. Yet, as Chilton (2014; also see Huggett, 2015b, Perry and Beale, 2015) makes clear, in these contexts, such tools have hardly been theorised; they tend to escape deep critique and evade systematic analysis of their political consequences, e.g. in terms of sustainability, equality, democracy, wealth and poverty. Following Huggett (2015b, p. 19), this 'means that the [digital] data arrive at the would-be user context-less and consequently open to misunderstanding, misconception, misapplication, and misinterpretation.'

Meanwhile, the opinions of digital archaeologists themselves on these matters seem often to be sidelined (after González-Tennant, 2016), relegated as they usually are to specialist publications (e.g. conference proceedings, digital-themed texts and journal issues) and going uncited in general archaeological theory. The predicament is an exasperating one, especially because digital archaeologists appear to be complicit in their own marginalisation.[6] For instance, in the inaugural article to the *subject-specific* journal *Frontiers in Digital Archaeology*, Costopoulos (2016) argues 'I want to stop talking about digital archaeology. I want to continue doing archaeology digitally.'[7] Costopoulos goes on to confess his shame over the field of practice of digital archaeology as a whole:

> 'I must admit that I am a bit embarrassed at the public expense involved in the numerous rather sterile meetings in which I have participated about the digital turn in archaeology and the setting up of public archives, community GIS, etc., for what so far I consider very little results. The carbon footprint of some of these meetings must have been stupendous...But I do not think the expense so far has been justified by the outcomes.' (Costopoulos, 2016)

Perhaps unwittingly, Costopoulos hints here at some of the very issues that 'doing archaeology digitally' has often failed to address — its financial burdens; its unequal deployment based on geography, education, ethnicity, language; its possible implication in structural violence and structural inequality; its gendered dimensions; its environmental impacts, carbon footprint and more.

Taking this latter point about environmental impacts to its extreme, as digitally-oriented practitioners, we invest in the media technology industry, which as Parikka (2014) outlines, has long sustained itself on civil war, child labour, resource depletion and environmental devastation, massive energy consumption, electronic waste and colonial occupation. Parikka describes this era as the 'anthrobscene', wherein media technologies and their enabling infrastructures effect obscene impacts upon the globe. Whether or not archaeologists care to enter into a debate about our culpability in nurturing the anthrobscene, our digital practice has global material and economic ramifications — yet these ramifications are regularly unaccounted for in the extant scholarship. In those cases where deeply political (digital) archaeology *is* being performed (e.g. by Hacıgüzeller, Morgan, Richardson, Tringham), it seems notable that such practitioners, firstly, are often not acknowledged for the depth, complexity and longevity of their theoretical contributions to the discipline; and secondly, are often female (see comparable argument in González-Tennant, 2016). Our preliminary scan of recent publications by digital archaeologists themselves suggests that these politically–committed individuals go less cited by their own digital colleagues, and — when cited — are attended to superficially, as mere champions of public or participatory approaches. Whilst a tentative observation, we would suggest there may be systematic bias presenting itself here which deserves further interrogation.

Bias extends straight to the core of general disciplinary theory, where the so-called 'grand challenges' of archaeology today (Kintigh *et al.*, 2014) appear to betray both a pervasive focus on archaeology as science (where our practice could be read as primarily a natural science: materialist, positivist and objective), and an absence of concern for archaeology as politics (as per critique by Cobb, 2014). Digital tools, when deployed in the name of addressing such challenges, arguably often underpin and worsen the predicament. For instance, as Jeffrey (2015, p. 149) puts it, 'Digital representations of the past continue to struggle to overcome the perception that they are either purely scientific tools for analysis and management or flashy and unnecessary demonstrations of technological prowess offering no real insight into or connection with the past.' Key disciplinary theoreticians actually seem unaware of the capacities of digital media and of long-standing digital archaeological experimentation with the senses (e.g. by Eve, 2012; Cooper, 2014), so much so that Kristiansen (2014, pp. 27–28) can be found writing,

> 'My own unfulfilled dream is that one day we shall be able to release the sounds of prehistory: talking, music etc. stored in some mysterious way in the atomic particles of pottery and metal during the process of their production. It will probably never happen...'

What seems evident here is that archaeologists might fundamentally misunderstand what the digital can and could do (both positively and negatively) for the discipline — and digital archaeologists themselves might be fuelling the situation. Borrowing from Reilly (2015, p. 230), 'The bar is seemingly set too low'. Not only are our expectations of the technology deficient, but so too are our assumptions about digital practitioners, digital research potential, and the socio-political impacts and implications of digital work. Yet there is no reason why this mindlessness need persist.

To draw from Dallas (2015, p. 178), 'by doing archaeology digitally it should seek...to make a difference to

[6] The irony is not lost on us that this paper itself is an output of conference proceedings.

[7] Not only does the journal's very name force a particular conversation about digital archaeology, but the parent organisation behind the journal, Frontiers, has been accused of predatory open access practices linked to its digital medium (Terras, 2015; Scholarly Open Access, 2016).

the broader epistemic and pragmatic contexts of archaeological work.' As we see it, our real challenge now is to draw together recent critical digital practice (as described above) into a more coherent rubric that testifies to the fact that so many archaeologists *are already* contributing to these contexts of work. We believe that, in so doing, we can proffer a more cohesive reflexive model for the digital age in archaeology. Beyond the authoring of such a rubric in the form of an academic article, which we hope to cooperate on in the future, we would also suggest immediate next steps might include:

1. Continued fostering of initiatives like digiTAG (day-long sessions of presentations hosted alternately at the TAG or CAA conferences), which aim to nurture broad discussion between digitalists and other specialists within archaeology. As a new collaboration between the TAG and CAA, digiTAG now needs a sustainable model to keep it active. Within the CAA, this might be framed as a Special Interest Group. Within TAG, it has been tentatively positioned as one among the "family" of TAG events, although its long-term management structure now needs solidifying.
2. Concerted contribution to training networks and international centres of best practice (e.g. the Norwegian DialPast research school) whose concern is for building cutting-edge, theoretically-engaged communities of practice, particularly amongst PhD students and early career scholars.
3. Investment in a series of synthetic volumes on critical digital archaeology, perhaps commissioned through digiTAG presentations or developed in concert with investment in training networks.
4. The development of a robust framework of reflexive practice for the application of critically engaged digital methodologies at a disciplinary level (in the vein of Hodder, 1997), which may culminate in good practice models and a series of theoretically grounded case studies.

Digital archaeologists are in a position to lead archaeological theoretisation overall. In fact, Huggett (2015a, p. 87) goes further, arguing for our cross-disciplinary relevance in terms of being 'best positioned amongst digital humanists to investigate and understand the implications, transformations, and repercussions of digital technologies.' We do not need to be simplistically reduced to wielders of big data or technical equipment. We do not need to be the subject matter relegated to medium-specific journals or conference proceedings. The CAA itself can — and should — be a go-to point for archaeology overall. We have the capacity, the tools, and the conceptual foundations to shape the future of the discipline. It is time for action.

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Ontologies and Standards

Mieko Matsumoto and Espen Uleberg (eds) 2018. ***CAA2016: Oceans of Data***
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
Oxford: Archaeopress

Is that a Good Concept?

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Abstract

This paper draws on the experience of the 20 years of development of the CIDOC Conceptual Reference Model (now an ISO standard) to look at what constitutes a good concept; that is, what are the characteristics of a concept that will form a robust part of a useful ontology.

It first discusses the nature of Knowledge Modelling and then the characteristics of Data, Information and Knowledge. The paper continues by identifying and characterising the four foundational elements of such a definition: Arena, Purpose, Intension and Potential. It then describes the four parts of the concept's Intension, namely Identity, Substance, Unity and Existence. It concludes with an empirical example of the application of these definitions.

Keywords: knowledge modelling, ontology, concept, intension, CIDOC CRM

Introduction

This paper explains the philosophical grounding and methodology adopted by the CIDOC Conceptual Reference Model (CRM) Special Interest Group (SIG) in the practice of knowledge modelling. While formal ontologies present the best known practical solution to the integration and aggregation of data from heterogeneous data sources, the implementation of such systems has been hampered by two problems. Firstly, they have been hampered by a lack of easily available and supported technological solutions for implementation and, secondly by a limited pool of knowledge modelling skills. Whilst the first of these problems has largely been solved with the recent surge in the availability and usability of triplestore and graph database technologies, the second remains an issue that needs to be addressed. Knowledge modelling can be viewed as a specialisation by itself, but it is most useful when undertaken by domain experts as only they can guarantee the proper translation of their original intent.

This paper aims to address a part of this knowledge modelling skills gap by introducing the principles adopted and developed by the CRM SIG. It starts with the concept of knowledge modelling and what it means. Next it explores the definitions and relations between the classic triad of data, information and knowledge. This serves as a necessary platform for introducing our methodology for robust modelling of concepts and relations through the definition of their Arena, Function, Intension and Potential. By robust knowledge representation we mean a model that is empirically grounded but sufficiently generalised, that it is both sustainable and can survive significant changes of context and user community. It concludes with a concrete example of how to apply this method to the development of an extension to the CRM ontology. The principles could equally be applied to the development of other ontologies.

What is knowledge modelling?

Key to the CRM SIG definition of knowledge modelling is a fundamental decision on how to approach the dialogue represented by the use of information systems. In contrast to a commonly held position within computer science going back to Shannon and Weaver (1949), the CRM SIG does not hold that the task of knowledge modelling is about signal transformation where the content of the messages being transmitted is irrelevant to the science of representing knowledge. To the contrary, the CRM SIG believes that the proper object of investigation of knowledge modelling is to examine the meaning of information as used by specialists and to attempt to develop suitable generalisations of these meanings so as to make explicit the general concepts adhered to within a particular domain. This work is undertaken in order to support interoperability between data sets by providing a common abstraction language for electronic asynchronous communication across a domain of users (Denning and Bell, 2012). It is this attitude of interest in the *meaning* of the discourse to be modelled and the corresponding position on the scope of knowledge modelling practice that differentiates the CRM SIG's knowledge modelling techniques. The CRM SIG believes that one cannot reduce the transformation and transmission of information to a mere mathematical problem, as the intention is to support communication between human beings, albeit mediated by machines. The activity that specialists engage in when they use information systems in documenting their work is not a mindless, grey process of inventorying but, rather, a task rich in meaning. Such information has the potential to enrich general scientific knowledge directly, but requires re-expression in a more general form that makes it economically and ergonomically feasible to access, compare and understand. The product of knowledge modelling can be seen as a high-level conceptual interchange language (Doerr and Crofts, 1999). Such a language becomes critical for the task of controlling, maintaining and above all understanding scholarly and scientific output as the sheer size and complexity of this output grows.

The basic KID terms from a knowledge modelling perspective

The argument gets ahead of itself, however, if the terms of the discussion are not clarified. In particular, much confusion and crossing of purposes rests around the mixed usages of the terms data, information and knowledge. Work has already been done in more general information sciences to attempt to clarify and hierarchically relate these concepts (Rowley, 2007) and analyse their statements about the nature of data, information, knowledge, and wisdom. The hierarchy referred to variously as the 'Knowledge Hierarchy', the 'Information Hierarchy' and the 'Knowledge Pyramid' is one of the fundamental, widely recognized and 'taken-for-granted' models in the information and knowledge literatures. It is often quoted, or used implicitly, in definitions of data, information and knowledge in the information management, information systems and knowledge management literatures, but there has been limited direct discussion of the hierarchy. After revisiting Ackoff's original articulation of the hierarchy, definitions of data, information, knowledge and wisdom as articulated in recent textbooks in information systems and knowledge management are reviewed and assessed, in pursuit of a consensus on definitions and transformation processes. This process brings to the surface the extent of agreement and dissent in relation to these definitions, and provides a basis for a discussion as to whether these articulations present an adequate distinction between data, information, and knowledge. Typically information is defined in terms of data, knowledge in terms of information, and wisdom in terms of knowledge, but there is less consensus in the description of the processes that transform elements lower in the hierarchy into those above them, leading to a lack of definitional clarity. In addition, there is limited reference to wisdom in these texts (Rowley, 2007). It is useful, therefore, to revisit and build on this work with regards to the specific requirements of knowledge modelling.

Data is the lowest level object dealt with in computer science. It is quite literally the bits and bytes that constitute digital objects. It may encode any number of potentially meaningful signs including but not restricted to: numbers, texts, lists, categories, or images. Data in itself, however, is not yet information. Rather, it is the equivalent of the sensory impressions of the physical world received by an observer. Raw data no more communicates meaning to an individual during discursive communication, than a wall does to an archaeologist during an excavation. There is something to learn from these objects; indeed the observation of such data or impressions is the empirical foundation of knowledge that supports reasoning and understanding. However, without being able to contextualise the data there is no meaning. Data, even if discretised into a symbolic structure, needs to be embedded in a discursive system to give it the interpretive potential that qualifies it as information.

Shannon and Weaver (1964) defined information as a sequence of symbols that carry a message and that can be transmitted as a signal. While it is common to focus on the information-as-signal element of this definition, in knowledge modelling it is equally important to focus on the information-as-message element. What adds to the plain signal the character of also being a message and thus information? For data to be taken as information it must not just hold discrete symbols but it also be enrolled into a discursive system by a human agent. This is to say that information is data, in a specified context, with a sender. It is a precondition that the sender and the potential recipient subscribe to, and depend upon, a particular context of discourse with all its inherent features, be they linguistic codes or epistemic norms, in order to be able to understand the message that has been encoded and transmitted in the signalling system. In the context of information systems, which knowledge modelling deals with, this situation is always plural; there are a multiplicity of senders and receivers in asynchronous communication. To maintain the information quality of this machine mediated human discourse, the multiple-provenances, both in terms of actor and context of elocution that gave the semantic weight to the messages, must be saved.

Whilst it is tautologically true that information can be held in an information system, it actually requires data to be stored as propositional statements. However, a proposition in itself is not knowledge. The elision of information and knowledge is an easily made error when undertaking knowledge modelling. Information is a potential input to a particular kind of factual or propositional knowing. Such propositional knowledge is the ability to interpret this information and then have a belief about how well the contained propositions represent the world at some moment in time.

To understand this, we must enter into the realm of traditional epistemological analysis. Propositions are not true or false in themselves, though they are meaningful (Wittgenstein, 1967). Information is turned into knowledge under specific conditions, traditionally known as justified true belief. The first step is for a knowledge agent to adopt a particular set of propositions and declaring that the set holds with regards to a particular state of the world. The second is that this should be verifiable for the world to which the knower binds the propositions. Lastly, the adoption of the set of propositions should be based on some justifying principles that are then open to scrutiny and revision.

Using this traditional analysis of knowledge when analysing knowledge modelling allows us to highlight some important points. Knowledge is a faculty that is specifically human and not, as yet, an algorithmic, deterministic process. An information system does not contain knowledge. It stores and provides access to the proposition sets that can be used by humans in gaining knowledge about a particular state of affairs. It may also provide some automated reasoning. Formal ontologies aim to support this in supporting the derivation of facts from a formally encoded reasoning system. Again such information only becomes knowledge after its adoption by some human agent, its assertion and its confirmation in a knowledge community through procedures of verification and falsification (Feyerabend, 1996; Kuhn, 1996).

This leads to a new understanding of what functionality is required in information systems in order to model and support discourse. The role of an information system is that of a communication tool that has the capability to induce knowledge under the right conditions. To do this it must not attempt to replicate the world, nor act as an artificial intelligence, in a strong sense. It must recreate the mundane situation where contextualised statements are interpreted as the same intended reality by multiple actors in an asynchronous communication environment. Only in this way, can an information system become an efficient part of both information storage and the active process of knowledge generation. Such a goal can only be realised where;

a. the information system allows the articulation of clear and unambiguous propositions;

b. the propositions saved and presented can be attributed to an actor so that the source of the proposition can be trusted, or not, and;

c. that the propositions are related to their context of articulation and the explicit rules of this context; such that there is a principled means by which to recreate the interpretation function that exists in two-way communication.

This re-addressing of the conceptual pyramid of data, information and knowledge within the context of knowledge modelling should eliminate basic misconceptions and clarify what the task for the knowledge modeller is. The knowledge modeller is not tasked with representing knowledge per se, nor with the management of raw data ignorant of the semantic framework within which it is formulated. Rather, the knowledge modeller working from data structures as empirical evidence must attempt to derive the conceptual frame within which these structures were created. This will allow the articulation of a generalised conceptual language for the domain that will allow the storage of correctly provenanced data-come-information in an information system.

What makes a good concept?

With this framework in mind, an answer to the question, 'what makes a good concept?' can be formulated. Over the last 20+ years of development the CIDOC CRM SIG has built a rich empirical base of experience that provides a best practice prescription for the generation of classes. The methodology presented here will focus not on the technical or practical steps of ontology construction in terms of gathering initial data, tool choice, planning and iteration — all extremely important questions in their own right (López *et al*., 1999; Sure *et al*., 2009; Uschold and King, 1995) — but rather focus on the conceptual elements required to build robust concepts and relations that allow for long-term re-use and which protect, as far as possible, against non-monotonic revision.

Conceptual elements

There are four elements which must be considered in the construction or extension of an ontology: Arena, Purpose, Intension and Potential. Using these four elements when declaring classes and relations enables a structured development path to a robust and sustainable ontology.

Arena: The first step when considering the concepts to declare in an ontology is to look at the scope of the ontology and understand the arena within which the concepts are to be applied. A formal ontology is a conceptual artefact that has a role to play in aiding reasoning of a particular type for a certain, perhaps broad, but always limited domain (Garbacz and Trypuz, 2013). This arena of operation is important to consider whenever investigating and declaring the classes of an ontology, as the semantic intension of any particular

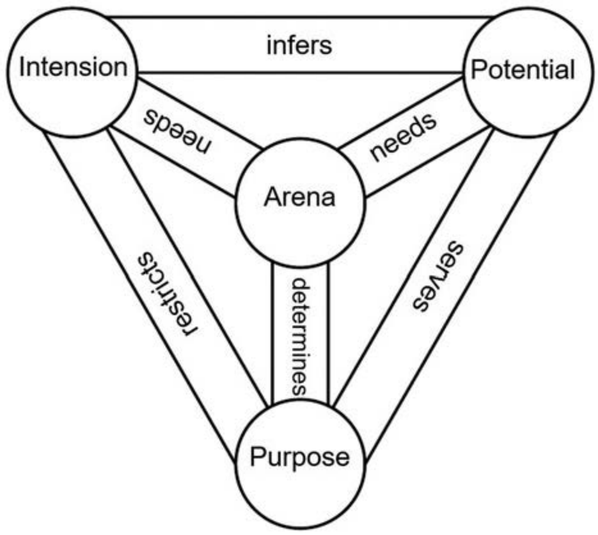

Figure 1. The four conceptual elements; Arena, Purpose, Intension, and Potential and their relationships.

concept will have different characteristics depending on the arena. The nature of the arena may vary both the meaning of the concept and the interesting set of relationships that it can have. For example, the study of cultural heritage is a science based upon the interpretation of possible pasts where the core interest is in making statements about the past relations of objects, ideas and people in time and space. In contrast the objective of experimental sciences like physics is to make predictions about future states of affairs. While both make appeals to concepts of time, for example, the use that they are put to, is different. In ontology production, the interest is not in providing a total model of the world, but an adequate model for the scientific picture of the world for a particular broad domain of research. Understanding the finite arena in which a concept is deployed and its use therein is crucial to the ontologist.

Purpose: Once the Arena has been identified the next step is to understand the restrictions that the Purpose imposes on the classes declared within it. All classes should be considered as playing a functional role. It is a common mistake, to think that the chief functionality of the declaration of classes is to enable the division of items according to a complete and exclusive division of the world. Classes in a good ontology, however, do not play this sort of simple taxonomic role. Rather, they are the anchor points for talking about the world in certain ways; making particular statements about relations between things. When thinking of a class, we should not ask the question 'what is it', but rather 'what does it enable me to say'.

In general, it can be said of any well-formed class that it will allow the collection of instances under its label. It must then be distinguished in which functional role in the discourse it is deployed: to support recall or to support precision. When defining a class to support recall it will tend to have a higher level of generality. This allows a user querying the system to find instances of the class that have potential behaviours, without yet being certain that they do, in fact, exhibit such behaviours. This guarantees that the information system will not 'hide' possibly correct answers from the user. Alternatively, classes may be declared to give a very specific indication of the behaviour of the instances that they stand as universals for. These classes support precision and in this case, the user should be able to trust an inference made about an instance of the class. There is a trade-off between recall and precision. The greater the precision a class offers, the less generalising recall it can support and vice versa. In resource finding applications, recall is always more important than precision.

Intension: Once the preparatory work of considering the Arena and Purpose for the concepts is complete the intension of the class or relation can be established. The intension of the class gives the qualities which determine if an instance can be subsumed under a certain class (Goldberg, 2007; Quine, 1951; Searle, 1983; Zalta, 1988). The methodology requires that, the scope note of the class, the description of what it is, should be based on the philosophical investigation of the intension of the class and not the extension of the class. That is to say that a class is not defined by the instances that make it up, the extension, but rather by an intensional definition. This definition explains the meaning of the concept to the ontology user and thereby allows them to identify from the always open set of all instances in the real world which would fall under the definition. Failure to support such identification indicates a problem with the definition. A robust intensional definition of a class requires explicitly specifying the Identity, Substance, Unity, and Existence conditions of members of the class.

The first part of the intensional definition is to give the identity criterion by which one can differentiate two instances of the same class (Wiggins, 2012). Such identity criteria are particular to the Arena in which the concept is to be used. Depending on the higher level domain, identity criteria can be given differently. For example, one can imagine an olive tree with a life history where a disease splits the tree, leading to the complete separation of the root structures and sapleading parts. Nevertheless, some parts of dead wood material still connect both systems mechanically. Whether this will be one or two objects under some tree class, for example, will depend on the functional use of the tree class within the discourse. If this class belonged to an ontology for supporting olive cultivation it may be that physical proximity is enough to declare the tree as one. If this class belonged to a biology ontology, it may be that the differentiation of root systems and therefore nutrients would support the argument for two instances. There is no overall 'right' identity criterion. There are only appropriate identity criteria for a particular Arena.

The second task of the intensional definition is to establish the substance of the instances of the class. The question here is to clearly indicate what instances of the class are made of. The substance of a class can be extremely varied, depending on the Arena of the ontology. So, for example, a poem is made up of a sequence of words, a cup is made of ceramic (solid matter) while an event is made up of change. Making clear the substance of an instance of a class is very important in avoiding mistaken attribution of instances to classes. A poem, for example, should not be confused with the physical text that carries it. Without a substance declaration, the job of identifying instances cannot go forward (Wiggins, 2012). It is also important in 'is a' hierarchies that the substance of classes within the hierarchy is coherent. For example, the substance of a subclass whose parent class substance is material, cannot be conceptual. This would cause inconsistency in reasoning.

Thirdly, the unity conditions of the class must be confirmed. That is to specify the conditions under which something can be considered as part of an instance of a class and when not; in other words, what comprises ONE instance. This is meant to aid the user in understanding, for example, if the knob is part of the door, is the verse part of the poem, is the charge part of the battle. These examples implicitly point out that unity is dependent on substance. Something can only be made up of parts which are of the same substance as it is itself. An idea cannot be made up of bricks. It is the unity condition that applies within the particular Arena that must be specified, since the distance of transitivity of unity will be important. The handle, for example, may be part of the door, but is it also part of the castle? The charge is part of the battle, or is it part of the war? The answers to these questions are dependent on the domain and should be settled as clearly as possible in the intensional definition.

Finally, in each intensional definition, the modeller should ensure that the existence conditions for instances of the class are clear. Under what circumstances does an instance of the class come into being and under what circumstances does it go out of being. It must be possible in an information system to state the times at which a described thing exists, and at which times it does not. These conditions can be very different. A poem, for example, could be said to come into being either through the conception of the poet, or the first time it is written down, dependent, again, on the Arena and Purpose. A definition for going out of existence could be that a poem goes out of existence only in the case every carrier of the information is eliminated; then the poem can be said to be lost.

Thorough specification of the aspects for parts within the intensional definition offered by the scope note of a class or property, gives the user of the ontology the requisite information to successfully identify instances of them. This full specification of an intension bearing in mind the Arena and Purpose of the class is also crucial to the modeller in the final and most important phase of the modelling exercise; that is determining the potential properties/relations of the class.

Potential: The most challenging aspect of modelling, however, is not the taxonomic declaration of classes but the understanding and specification of the potentials of classes. The intensional definition of the class coupled with the Purpose and Arena allow the modeller to establish what can be said about a particular class and therefore what might be reasonably inferred from it. Where a class belongs in the ontological hierarchy depends upon what might potentially be said about it, that is to say to which general category of thing it belongs. Then, depending on the specificity of the class, the differentiating relationships which required the declaration of the class can be ascertained. This aspect is a key principle in determining if a class needs to be declared. The transition from intension to potential constitutes the functionality of a class in the discourse. If there are not specific properties that hold for and can only be asked of this specific class, then there is probably no reason to declare the class. Usually such potential 'sub-types' can be dealt with adequately by reference to a controlled vocabulary.

Empirical experience and a review of the methodological literature suggest that the above theoretical considerations and actions form a highly valuable guideline for constructing principled ontologies. The resulting ontologies will be coherent, extensible and will serve the user community by allowing them to make relevant queries in an intuitive way. They will potentially also benefit from automated reasoning decisions enabled by the formalisation.

Example of the method in use

It is common within cultural heritage databases for there to be a table for the description of 'finds'. When considering the concept of 'the find' within the CIDOC CRM family of standards it is a common interpretation to understand the 'find' as a subclass of the class E19 Physical Object. The argument for such a declaration is the uniqueness of the find object, as not just any object, but a special class about which users may wish to reason in a way that differs from other more general E19 Physical Object instances.

The CRM SIG approach helps to show why this is an incorrect modelling decision. When considering the Identity, Substance, Unity and Existence conditions of the 'Find', it cannot be seen to be any different to any other instance of E19 Physical Object. The act of finding the object does not bring the 'Find' into Existence. In Substance, the 'Find' does not differ from any other physical object; it is material. The same principles of Identity for generic physical objects hold for the 'Find' as well. The same condition for going out of Existence, material destruction, holds just as true for a 'Find' as any other material object and is not altered or influenced in any way by being a 'Find'. So a subclass 'Find' would be a bad class declaration because of the inability to distinguish an instance of the new class from any other instance of E19 Physical Object that was not an instance of the new class.

However, the intuition that, relative to the Arena of archaeological investigation, there is something unique to be said about a 'Find' seems correct. What are the potential relations of the E19 Physical Object class? Is 'Find' a thing, or what new relations does it infer? What, uniquely, can be said about the relation between an object found and the finder? What interesting questions are there with regards to the found object? What concerns us is not the object, but the finding of it; so an event bound to the object through a relation of finding.

So to handle the question of a 'Find', it is necessary to declare a relation and some appropriate linked class to document the discovery event which brings the object into a sphere of knowledge in some way. Here, again, the application of the modelling principles can help with the definition of this new class. Suppose the requirement is for a relatively high level concept to be able to cover all kinds of finding activity, be it digging or field survey. If the class is defined by some sort of discovery concept, some addition to knowledge, then there are identification difficulties. Finding for one party, is not always finding for another.

The primary interest of reasoning is not the change of knowledge per se but the fact of existence of the 'Find' at the place and time of finding; the position within a context, regardless of who did or didn't know about it previously, is what the archaeologist will use to argue about activities in the past. A 'Find' is not a thing but indicates a relation of observation of a certain object under certain contextual conditions that allows for a reasoning process with regards to its history. The term 'Find' appears to be a naïve compression and reification of meaning into an object that in fact holds an entirely different underlying scientific relevance.

This analysis enables the proper treatment of the subject and the correct conceptualisation of the class. A 'Find' is not a thing but a relation of finding associating some people at some time and place in what can be understood as an encounter event. Thus for the proper documentation of 'Find', what should be added to the model is not a subclass of the physical thing, from which the find object differs in no significant way, but rather an event class that allows the documentation of a moment of encounter. From this can be identified the potential properties to record evidence of the presence of a particular thing in a particular context at a particular time and understanding who witnessed the fact and may have further knowledge about it. Its Identity, Substance, Unity and Existence are confined to the documented physical meeting of an observer with a particular object. In declaring such a class, S19 Encounter Event, in the CRMsci extension of the CRM for scientific processes, unnecessary and arbitrary extension of material classes is avoided. This also serves to systematically eliminate problems for information aggregation by always using the checklist of Arena, Purpose, Intension and Potential when making class declarations. The concept of 'encounter' not only adequately describes the archaeological concept of 'find', but also the biodiversity concept of 'occurrence' and equivalent notions in geology, palaeontology and anthropology. Thus by recovering the salient properties of discourse from the intuitive prototypical situation of the digging archaeologist, a surprising generalisation to other fields is gained.

Conclusion

This paper shows a practico-theoretical approach to ontology modelling built upon the best in ontology design literature and the testing of these principles in the empirical modelling work of the CIDOC CRM SIG group over the last 20 years. The first part presented an understanding of knowledge modelling and its task, specifically delving into the differentiation between data, information and knowledge. It also looked at the nature of information systems and how they can support knowledge sharing practices. This introduction served as the groundwork to present a practical checklist of considerations to use in the construction of extensions of an ontology. It was intended for both formal ontology specialists and domain experts working with such specialists and detailed an intellectual process by which they can measure their ontological modelling efforts against a scientific goal. It should help prevent obvious mistakes while supporting the building of robust models for the capture and sharing of information at a broad global scale. In contrast to the common computer science interpretation that regards the task of ontology engineering to be the transformation of conceptual intuition into a set of logical rules, the approach requires an additional step of the recovery from expert intuition of the actual properties of the reference world relevant to their discourse, before describing them in formal terms.

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Mieko Matsumoto and Espen Uleberg (eds) 2018. *CAA2016: Oceans of Data*
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
Oxford: Archaeopress

Sculptures in the Semantic Web
Using Semantic Technologies for the Deep Integration of Research Items in ARIADNE

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Abstract

One important goal of the EU-funded ARIADNE project is to integrate heterogeneous data originating from archaeology and related fields. One strategy is to incorporate descriptions of vast amounts of research resources into a shared ARIADNE catalogue. In this paper we pursue a complementary strategy, namely an experiment on the tight integration of detailed descriptions of single items of research. We describe a practice-oriented approach to dealing with heterogeneous data with the help of Semantic Web technologies and present a specific use case about sculpture and the integration of archaeological finds from various databases. We highlight some of the difficulties in integrating databases with differing origins (museum catalogue, object database, excavation database) and therefore different terminologies, foci and languages. The integrated data sets will be accessible via a unified programming interface, which allows rich querying possibilities. This interface lays the groundwork for a user interface that facilitates intuitive queries for accessing the integrated data.

Keywords: semantic modelling, data integration, semantic web, sculpture

Introduction

The primary goal of the EU project ARIADNE is to bring together and integrate existing archaeological data infrastructures to offer researchers unified search and discovery over a wide range of distributed data sets, which is very much needed in archaeology. In addition to the aggregation efforts that resulted in a general catalogue of archaeological resources in the ARIADNE portal,[1] several case studies examined a tighter and semantically richer integration using Semantic Web technologies. The common ontology used in these scenarios was CIDOC-CRM, which was adapted and extended for domain-specific use in archaeology by the extension CRM-ARCHAEO. In addition, common terms for time, space and subject specific terms needed to be harmonised and brought together.

This paper aims to present one such case study and describes the technical process of integrating four heterogeneous databases as a proof of concept for creating a rich common repository with item level granularity. We will give a summary of the general procedure including a small presentation of the different data sets, the aggregation workflow and the usage of CIDOC-CRM as a common ontology, the integration of the harmonised data within a triplestore and the Linked Open Data enrichment, which is necessary to gain real interoperability. In addition, two different small use cases that describe how the data can be used and accessed using SPARQL will be demonstrated. The first highlights how the Knowledge Graph can be facilitated to tremendously enhance literature discovery. The second shows how the data itself can be used to detect errors and discover dating knowledge. The data used in this scenario covers Greek and Roman sculpture. The data sets are coming from four different databases covering museum, archive and excavation data.

The presented queries are based on two scenarios. The first query centres on a fragmented white marble head of a satyr that was found at Chimtou (ancient Simitthus, modern Tunisia). The second query provides an overview of several types of statues and other objects found at a single archaeological site and made of pentelic marble that was quarried near Athens. Both requests will show advantages and chances for archaeological research and further scientific investigation.

Integrating sculpture data sets

Research on sculptures is very traditional and highly embedded in the context of museums. Even though the museum community under the hood of ICOM's

[1] http://portal.ariadne-infrastructure.eu/

'International Committee for Documentation'[2] has developed many different metadata standards like LIDO or CIDOC-CRM for data exchange, there are not many subject-specific standards established for the description of sculptural objects. In the following we briefly describe the data sets we have selected for our work. Only databases with permissive licenses and where the data could be extracted with reasonable effort were taken into account.

Agora

The American School of Classical Studies at Athens started systematically excavating the Athenian Agora in 1931. The database[3] for the project is a single integrated online accessible archive to all the different resource materials; the current digital-born excavation documentation, finds, architectural plans and drawings, reports and publications. Prior to that, the documentation relied on four different notebooks, which were digitised and annotated. All the objects are documented and mapped to the Dublin Core standard and allow search and open access to over 355,000 objects, created over 85 years of research activity.

The Solr4 powered online database offers an XML export, which was used to extract more than 1000 sculpture objects. These objects are highly contextualised with all other available sources, from which 1700 archaeological contexts and 56,000 bibliographic references to more than 240 documents were selected.

iDAI.objects Arachne

iDAI.objects Arachne[5] as the central object database of the German Archaeological Institute provides researchers with a free online search tool. Originally started in 1995 as a Filemaker database, it was intended as an image database for sculptures from the research archive for antique sculptures (Forschungsarchiv für Antike Plastik) at the University of Cologne (Scheding, 2014, p. 38). In 2004 the database migrated to MySQL and extended its focus to all kinds of archaeological objects. Currently in its fourth version, the database holds more than 3.6 million objects with associated metadata. All 83,085 sculptures in Arachne are from the Roman and Greek classical periods, mainly obtained through research project data, digitisation of archives and museum collections, like the complete Catalogue of Sculptures in the Antiquities Collection of the Berlin State Museums (Antikensammlung der Staatlichen Museen zu Berlin). The majority are of excellent quality, as the sculptures contain detailed descriptions and are contextualized by more than 1000 archaeological types and 88,000 bibliographic references with links to the literature catalogue Zenon6. Arachne's data is mapped to CIDOC-CRM and made accessible through an OAI PMH interface7, which was used to harvest the above mentioned data in RDF/XML format.

British Museum Collection Online

The British Museum Collection Online Database currently provides access to around 2.28 million records. Digitising the collection is still ongoing and aims at whole coverage; that is a record of every object in the Museum collection, with corresponding scientific and conservation metadata. The data is also exposed for Semantic Web use as a SPARQL service,[8] which provides access to all objects in the Collection Online. All data is mapped to CIDOC-CRM and the British Museum is following the Linked Open Data approach for their thesauri. For this scenario, 52,000 openly available sculpture records were used.

iDAI.field

Since 2005, the field research documentation system iDAI.field (Schäfer, 2012), which is based on the commercial software Filemaker, was developed and maintained by the German Archaeological Institute (DAI). It provides a very complex information model. It supports modules for documentation of excavations, surveys, building studies, iconographic studies, material studies, restoration work and scientific sampling, which can be adapted for project-specific needs. Currently iDAI.field is in use by around 35 field research projects from different universities and the DAI with a total number of over 1 million data sets. For the current approach we included the data set of the database of the Chimtou project[9] with around 500 stone objects, including sculptures, which were found in roughly 120 archaeological contexts. The data was exported by using Filemaker's export functionality, which supports the XML format.

Bringing the data together

As can be seen in the description above, two data sets are provided in XML format, one from an offline relational client-based database (iDAI.field) and one from an interface of an online database (Agora). The Arachne data set is directly provided by the OAI-PMH interface mapped to CIDOC-CRM in RDF/XML format, while the CIDOC-CRM mapping of the British Museum Data could

2 http://network.icom.museum/cidoc/
3 http://agora.ascsa.net/research?v=default
4 http://lucene.apache.org/solr/
5 https://arachne.dainst.org/

6 http://zenon.dainst.org/
7 http://arachne.uni-koeln.de/OAI-PMH/oai-pmh.xml?verb=Identify
8 http://collection.britishmuseum.org/
9 https://www.dainst.org/projekt/-/project-display/33904

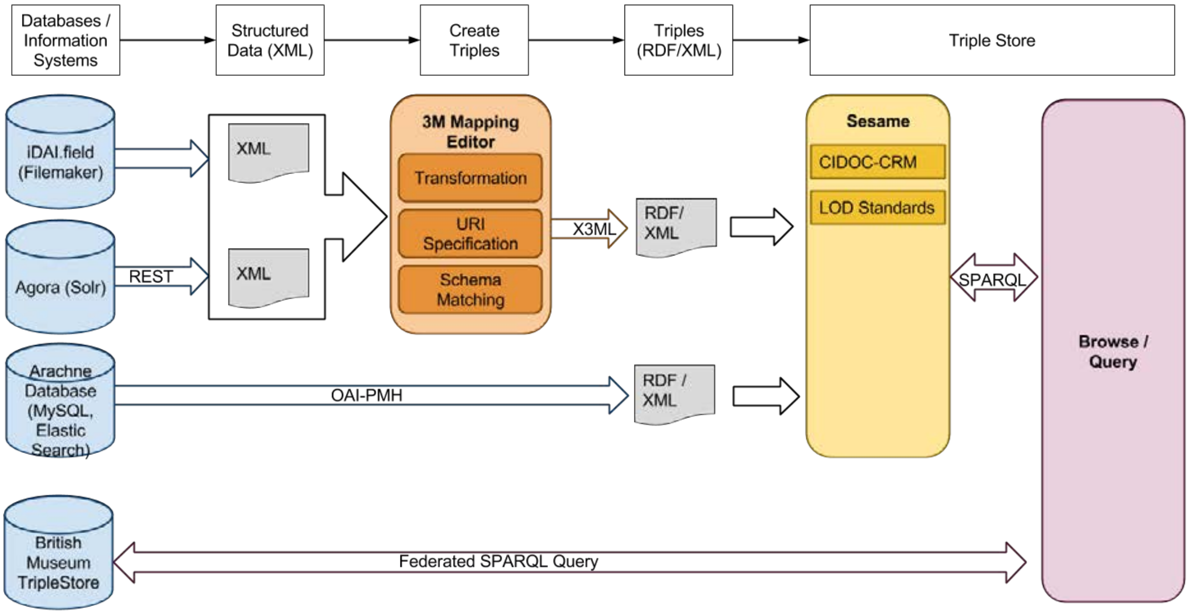

Figure 1. An overview of the data extraction process for the four sculpture data sets.

be accessed by the provided SPARQL Endpoints. How do these different data formats come together?

First of all, one needs to transform the XML data into triples in RDF/XML format using CIDOC-CRM (see Figure 1). This could be done by using a mapping and transformation tool like the 3M Mapping Memory Manager[10] maintained by FORTH. This Online Tool is used for describing and editing schema mappings in a human and machine readable way. After importing the XML data into 3M, three more steps are necessary (Doerr *et al*., 2015):

- Schema mapping: in this first step mappings are produced from attributes in the source schema (data set) to classes in the target schema (CIDOC-CRM). Therefore domain knowledge about the explicit and implicit semantics of the information model, as well as technical understanding of the ontology and the system are needed.
- URI specification: in the next step it is necessary to assign an appropriate URI to each resource in the data set. In an ideal world you could link directly to stable URIs of the integrated data source, if the data is available online. In the case of data only available offline like iDAI.field data, it is only possible to create pseudo-URIs.
- Transformation: in this final step the transformation of every source data sets record to a set of appropriate RDF[11] triples is done.

After these steps are applied the RDF triples can be imported into a triplestore. We tried different triple stores, and Blazegraph[12] was chosen in the end, as it provides very good performance and usability even with more than 5 million triples. The data could be imported using console scripts, which should be applied for bigger data sets, and a web based GUI-based import.

Once the data is imported into the triplestore, it could be enriched using Linked Open Data web resources as described in section 3. Technically the enrichment works with a mapping of the source terminology to the target terminology, which should be referenced by URIs of web resources. The individual triples could be changed directly within the triplestore using SPARQL Update.[13] Another approach is the manipulation of the triples in RDF/XML before importing by using XSLT, any other programming language, or by just using a text editor with REGEX functionality.

With the described procedure, overall four different data sets with four different preconditions were integrated. It shows the flexibility and the usefulness of the tools used.

Linked Open Data enrichment

The use of ontology alone does not automatically lead to integration of different data sets; the ontology just describes the semantics of the information model. The values and terminologies used will still be diverse in terms of different spellings, errors and languages. For instance, a site name can differ from data set to data set. Therefore it is ultimately necessary to refer to online resources that act as standardisation tools instead

[10] http://www.ics.forth.gr/isl/3M/
[11] https://www.w3.org/RDF/
[12] https://www.blazegraph.com/
[13] https://www.w3.org/TR/sparql11-update/

of text strings wherever possible. We have identified different cases where standards could be applied, which will be explained in further detail.

Places

The location of a find or the different spellings and the position of an archaeological site are fundamental information used by many systems. Therefore it is of great importance to provide systems which offer a referable URI for the desired location with different language representation, spellings and location. The concept of gazetteers as a reference system is quite old and was adopted early-on by archaeology (e.g. Clark, 1932). It is quite straightforward to enhance them semantically. In terms of standardisation, location has benefited most from the work, which has produced a number of useful possibilities:

- Geonames[14] is a geographical database of worldwide place names and offers access to over 10 million place names, which are categorised into nine different classes. It has a generic approach and offers very dense data about recent populated places. However, archaeological places are quite sparse. For example, Geonames provides only 117 archaeological sites in Greece.[15]
- Pleiades[16] was started in 2006 as a digital representation of the Barrington Atlas of the Roman and Greek World, but was adopted soon after for a wider scope. With 35,000 ancient sites it is now the largest gazetteer for the ancient world.
- iDAI.gazetteer is a gazetteer developed at the German Archaeological Institute which provides more than 1 million entries describing modern and ancient places that are of interest to archaeology, and also acts as a hub by linking other Gazetteers like Geonames and Pleiades. Its scope also includes geographic data recorded at site or building level, which is particularly useful when connecting different archaeological databases that overlap in geographic coverage.

Time

Temporal information is as important as spatial information. For the work described in this paper we have not used a time gazetteer, but we intend to do so in the future. There are a few time gazetteers available.

- PeriodO[17] is a large time gazetteer with a pragmatic data model for the Semantic Web. The ARIADNE project has both contributed to the PeriodO data model, and used the gazetteer within the portal.
- iDAI.chronontology[18] is a time gazetteer which is being developed at the German Archaeological Institute. It has a more complex data model which distinguishes between the definition of a period and the dating information based on this definition.

Literature

Standardisation in the context of Libraries has a long history, beginning with in-house rules for a specific library and leading to the current close cooperation between libraries (Thacker, 2000). To this end metadata standards like the MARC21 and international identifiers like the *International Standard Book Number* (ISBN) were established. ISBN numbers, with their introduction in 1972 as the ISO standard 2108, are commonly accepted and used. Unfortunately older publications don't have ISBN numbers, and as the registration is fee-based, smaller publications and specialized books are often published without ISBN numbers. Therefore the registration isn't possible.

There are a lot of authority control services for books, for example WorldCat.[19] However, Zenon with its focus on *Altertumswissenschaften* and entries for individual articles was the most obvious choice. Zenon is the bibliographical catalogue of the German Archaeological Institute including the data of all DAI libraries, the DEI Amman and the Winckelmann Institute. The resource was used for the use case since it is one of the biggest databases for classics with more than 1.2 data sets, and also covers books, e-resources, maps and archival material. The metadata standard Marc21 is used and URIs are provided.

Archaeological terminology

In general there are two different approaches for archaeological terminology. One could classify and define the terminology for all of archaeology and classics in a very generic way, or one could try to define a terminology only for a very subject-specific subset. There is always a trade-off between scope and precision. A combination of both procedures, where the specialized terminology links to the more generic terminology with some overlapping terms could be a hybrid solution.

Even though there is a lot of specialised vocabulary in use by bigger institutions, they often do not provide their vocabulary or it is not available in an appropriate format. The British Museum's vocabulary is already provided in Semantic Web formats, but unfortunately,

14 http://www.geonames.org/
15 http://api.geonames.org/search?featureCode=ANS&maxRows=1000″&country= GR (Accessed: 13.07.2016)
16 http://pleiades.stoa.org/home
17 http://perio.do/
18 http://chronontology.dainst.org/
19 http://www.worldcat.org/

as Gruber and Smith (2015, p. 207) have already stated, they are not linking to external vocabularies, which makes the integration with other data sets more complicated and the data sets and the vocabulary an open but isolated island. The specialised vocabulary of Arachne, which is particularly useful for the descriptions of objects, is currently being made openly available by iDAI.vocab, which is described below.

- Specialist Ontologies: the terminology of Nomisma.org[20] for describing coins and the evolving terminology of Kerameikos.org[21] for describing Greek ceramics are readily available in Linked Open Data formats. They also provide links to more generic terminology, which allow easy integration of the specialised data sets.
- The Getty Arts and Architecture Thesaurus (AAT)[22] is a highly evolved thesaurus for the humanities. It offers a lot of different branches following ISO standards, but as it follows a generic approach, it lacks specialisation. There are also other languages supported, but languages other than Dutch and Spanish are minimal.
- The iDAI.vocab[23] is a thesaurus of archaeological terminology which is currently available in 14 different languages. Its aim is to collect and organize the terminology used in the services of the DAI. The German thesaurus operates as the central hub: a German term, for instance, is linked to translations to all the available other languages. The concepts are classified according to the relations specified by the SKOS standard. In addition, the iDAI.vocab provides a web interface where users can easily look up a concept and investigate its relations to terms, translations and Linked Data from other resources. The words are connected to the equivalent concepts in other reference works, such as the Getty's AAT and Dbpedia.

Actors

Actors are of importance in archaeology for specific find categories, such as the issuer of a coin, who is generally named on the object, or actors mentioned in inscriptions or iconographic items. These actors are not necessarily real historical persons; they could also be mythological characters like the deities of the Greek mythology.

- The Virtual International Authority File (VIAF)[24] is the biggest international authority system for persons, which combines several reference data sets and maps them to the same person. Its data is mostly derived from the different library systems and thus works well for real historical persons and writers, which can be referenced by URIs, for example http://viaf.org/viaf/60280417. However, the information about mythological actors is very sparse and contains many duplicates.
- Wikidata[25] is the data backbone of Wikipedia. It contains a lot of mythological characters and is currently, together with DBpedia, the best resource available. It's also 5-star Linked Open Data as it contains links to other resources, e.g. https://www.wikidata.org/wiki/Q163709.

Gazetteer of Stone quarries in the Roman World

For our second use case we added a list of marble quarries to our data. Since we also extracted additional information, this data is a hybrid between the sources of 'pure' content described and the authority control services in this section.

The online study published by Ben Russell in 2013 is currently the most comprehensive collection of ancient marbles.[26] It is operated and hosted by the Oxford Roman Economy Project. We included all 794 quarries of the data sets via the transformation of the PDF document to structured data in the form of CSV, which was in turn transformed to XML. The information submitted consisted of site, coordinates, location, country, former affiliation to Roman imperial province, a short declaration of the material and its characteristics and the most important literary sources. This overview is suited for an inventory and common basis if we also point out some minor problems in the terminology e.g. the occasional lack of some ancient terms in favour of using modern ones that are probably more famous.

Query Possibilities

Knowledge graph

Once all the standards above are applied and the data is imported into the triplestore, the full knowledge graph (see Figure 2) is accessible for further investigations of the data.

As a common ontology we have chosen CIDOC-CRM, as it is a widely accepted and used ontology in the realm of museums and gaining more importance in digital humanities as well. Besides the CIDOC-CRM Core there are also extensions which can be used if required by

[20] http://nomisma.org/
[21] http://kerameikos.org/
[22] http://www.getty.edu/research/tools/vocabularies/aat/
[23] http://archwort.dainst.org/de/vocab/
[24] http://viaf.org/
[25] https://www.wikidata.org/
[26] http://www.romaneconomy.ox.ac.uk/databases/stone_quarries_database/ or as PDF: http://oxrep.classics.ox.ac.uk/docs/Stone_Quarries_Database.pdf

Figure 2. The schema of a knowledge graph.

the data. We have used CRMsci[27] and CRMarchaeo[28] for describing scientific data acquisition and archaeological excavation processes. Furthermore we used the ontology Functional Requirements for Bibliographic Records (FRBR) for describing the bibliographical records and the W3C Basic Geo vocabulary[29] for simple geometry description.

Before applying a unified query over all integrated data sets, the mappings needed to be harmonised. Smaller differing mappings, needed to be harmonised, like the assignment of measured object dimensions. For the Linked Open Data enrichment (see the previous

[27] http://www.ics.forth.gr/isl/CRMext/CRMsci/docs/CRMsci1.2.3.pdf

[28] http://www.ics.forth.gr/isl/CRMext/CRMarchaeo/docs/CRMarchaeo_v1.4.pdf

[29] https://www.w3.org/2003/01/geo/

section) we have chosen Wikidata for actors, Getty AAT and Wikidata for archaeological terminology, Zenon for literature and iDAI.gazetteer for places.

Archaeological questions

The object-centric query is about a fragmentary head of a Satyr that was found during excavation at Chimtou in November 2010 (Scheding, 2013). First the object was registered in iDAI.field and afterwards in iDAI.objects Arachne.[30] The extent of the head, the designation as a Satyr, the stylistic and iconographic creation and the material named as white marble are facts that could be useful in finding comparable objects. The aim is to learn more about the exemplar at hand, to get information about other exemplars, and to get an overview of quarries where the same kind of marble (white marble) was produced. If our research question is, for example, to search for comparable Satyr statues and the "type" that is shown by the fragmentary head, the parameters for a query can be defined as:

- Extent: under 1.15 m height
- Material: white marble
- Term: Satyr head

For the technical fulfilment of the query, it was necessary to enrich the triples within the triplestore with Linked Open Data standards using SPARQL Update. All terms for the material were linked accordingly to appropriate Getty AAT terms by creating new triples. While the actors represented on the sculpture were normalized by using Wikidata as a common standard. For example:

<http://arachne.uni-koeln.de/entity/1092353>
crm:P45_consists_of <aat:300011599>
<http://arachne.uni-koeln.de/entity/1092353>
crm:P45_consists_of <wd:Q163709>

After these standards were applied, it was possible to apply the same query for all integrated databases. This was the basis of a prototypical user interface (see Figure 3). The SPARQL query excludes the federated queries for the British Museum as their SPARQL endpoint was not accessible during the preparation of this paper. The presentation of the results was realised by the mataphactory platform.[31] Metaphactory provides a basic semantic data integration by offering a wiki system with widgets, which access the triplestore Blazegraph in the backend. It can be used to visualize the SPARQL queries and to easily construct user interfaces.

The results provide us with several comparably obtained, reconstructed or fragmentary statues that already point to the fact that the Satyr head from Chimtou can be assigned the type 'Ludovisi'. The next step would be an evaluation of the most suitable objects by further research filters in a new query or the matching of 'pairs, copies and correspondences' to evaluate the most likely type, which is in the context of the Satyr found at Chimtou the Ludovisi type, with many comparable exemplars from numerous countries, especially in Italy but also from the Greek island of Rhodes.

Furthermore, we could have a closer look at the marble. It is difficult to determine the origin of a white marble, especially in the case of Chimtou, where no white marble quarries with a texture like the Satyr head was available. Thus it is clear that the marble was imported. From here we come to our second query that is now site-based. In this case there is an important opportunity offered by queries which relate to quarries. If our query deals with the question of an overall spectrum of one single marble, we can formulate new parameters. We chose the pentelic marble,[32] one of the most popular ancient marbles with a white surface, and want to get an overview of statues made of this marble (see Figure 4).

- Material: pentelic marble
- Extent: bigger than 0,70 m
- Term: statue

For research purposes, literature references are essential. Normal bibliographical systems offer at best a thesaurus to tag the bibliographical data sets. This approach is limited by the extent of the thesaurus used, and for this specific use case one could only search for literature containing information about sculptures. The use of the knowledge graph could enhance literature queries and further investigation as it allows a more precise query. In the quarry use case, the knowledge graph is used to show all literature which contains information about sculptures made of pentelic marble, with 393 hits. Aggregate functions like the counting of documented sculptures made out of pentelic marble from specific literature offer a further hint to which literature might deliver the best result.

Our query delivers many objects in an overview from every database that is made of pentelic marble. It becomes obvious that pentelic marble has been used in antiquity over a considerable time-span to produce statues and sculpture of every kind, mostly by the Athenian workshops. This can be a starting point for further queries.

[30] http://arachne.dainst.org/entity/2295540
[31] http://metaphacts.com/

[32] http://archwort.dainst.org/de/term/6273, http://www.getty.edu/vow/AATFullDisplay?find=&logic=AND&note=&subjectid=300011599

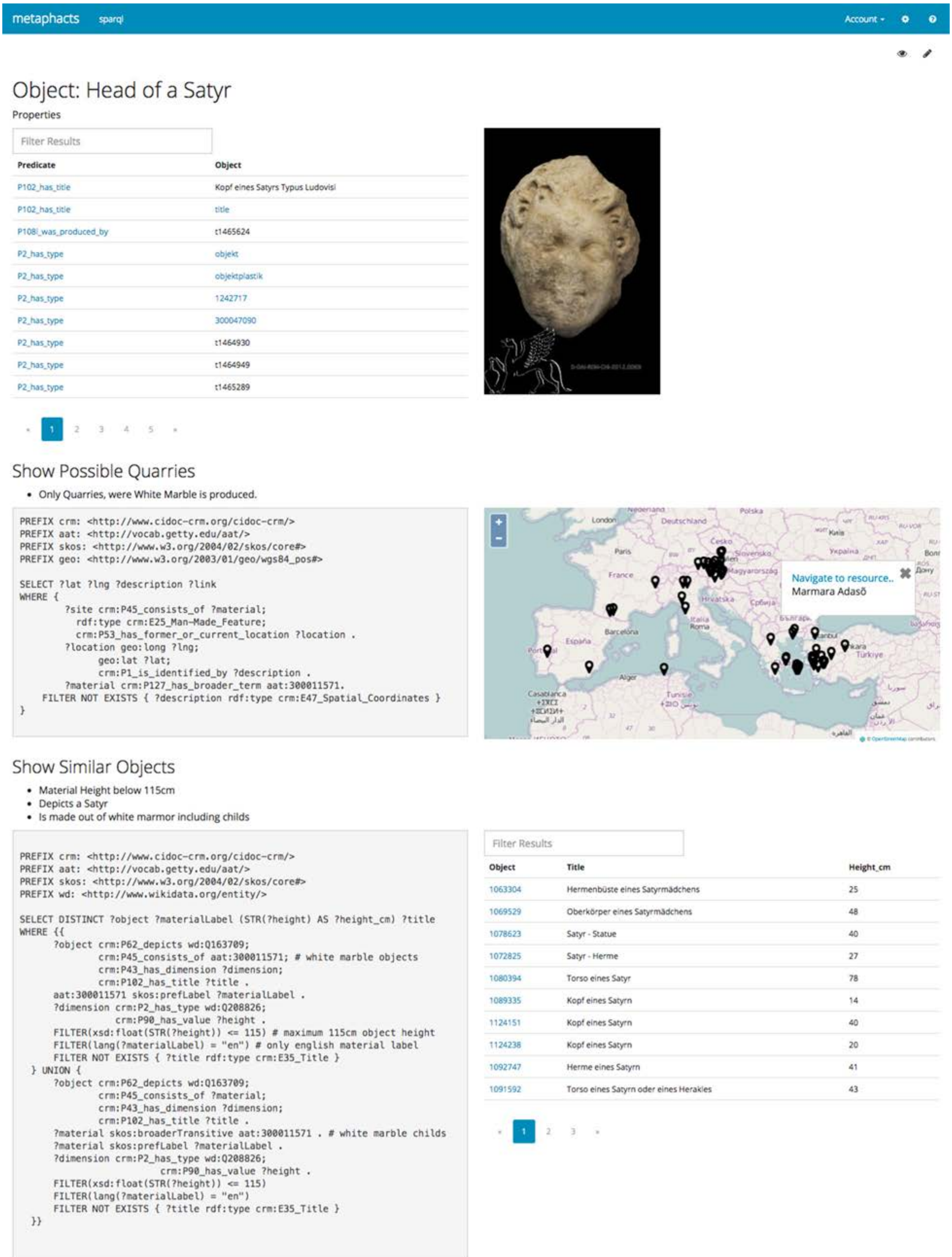

Figure 3. A prototypical user interface for queries over several databases, with a search for Satyr head made of white marble.

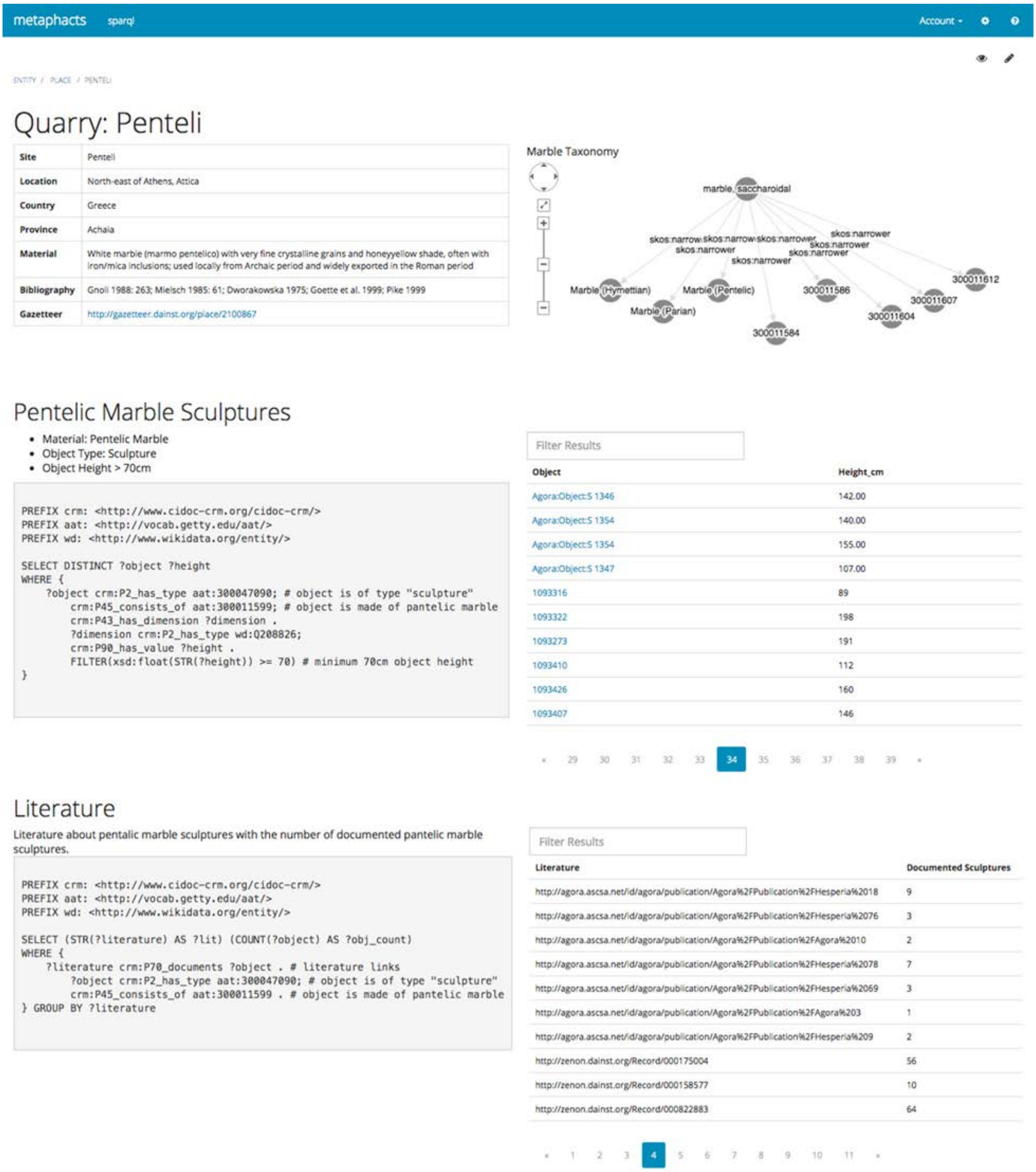

Figure 4. Searching for statues made of pentelic marble.

Bringing the data together creates a few challenges. For example, there are some remarkable differences in the terminology of the different data sets. We want to point out two problems we have observed. For ancient marbles there are not many differences that cause problems, but the terms used for the huge quantity of marbles in databases differ by using the ancient and modern names. Also, while the Getty AAT[33] and iDAI.vocab[34] provides useful categorised and multilingual overviews of many marbles, the British Museum Collection notably mentions only the parameter 'marble' without further details. For example, a query with the parameters 'sculpture' and 'giallo antico' will deliver matches in every data set, but if we are using 'marmor numidicum' — the literary-based ancient

[33] http://www.getty.edu/vow/AATHierarchy?find=&logic=AND&note=&page=1 &subjectid=300011571

[34] http://archwort.dainst.org/de/term/2383

name — instead of 'giallo antico', e.g. the Arachne can cope with it but we won't get the data from the British Museum Collection. The same heterogeneous approach as in the data sets is already present in the archaeological research literature. A recently published and already widely accepted collection of ancient marbles was published by Ben Russell in his 'Gazetteer of Stone Quarries in the Roman World'[35]. But a problematic aspect of Russell's study is the occasional absence of ancient names of some marbles that are known from the literary sources, while other studies that were fundamental for the data sets in the last decades used these *termini technici* consequently (For instance Gnoli, 1971; Schneider, 1986; Maischberger, 1997). Thus we have a serious inconsistency in older and younger data sets.

On the other hand, there are missing or inconsequent standards for the measurement of statues and objects in the archaeological terminology. Particularly in the context of sculpture, qualitative terms are often used to describe the size of statues rather than quantitative ones, which state a more precise measurement. For instance, the classifications of 'life size', 'under life size', 'larger-than-life' or twice and triple larger-than-life don't have a common or unique value. For example, there is a statue of a woman presented as 'The Large Herculaneum Woman type'[36] from Antalya that is 1.80 m large, but is registered as 'under-life size'. A single query with the parameter 'life-size' currently provides 4873 objects in the British Museum Collection that are not comparable in their size at all.

These differences can cause huge problems in a query that will sometimes deliver faulty and incomplete results. If there are no common standards or agreements for the terms mentioned above and further problematic terms, the use of overview data queries and further research will not be helpful within these categories.

Conclusion and further work

We have successfully integrated four different data sets with four different procedures for data handling. In future, it will be very helpful to host the source data, i.e. four star linked data as described by Tim Berners Lee, as a web resource with stable URIs. With the data flow that we have described, the origin of the source data does not matter as long as it is possible to export the data into a structured data set using a non-proprietary open format. From an archaeological view it is desirable to work with standards and declarations in many languages and countries that are as similar as possible.

Combining databases and the transparent structuring of the databases gives rise to powerful tools in the daily work of an archaeologist working on excavations, survey data or museums and collections. The easy access to a huge amount on comparable data with one single query and the further processes in filtering and dealing with these kinds of information offers great opportunities to all archaeological and interdisciplinary areas of expertise. In fact, the possibilities ARIADNE provides for archaeologists should be applicable to a much larger number of research fields.

On the data side we are planning to refine our use cases by adding links to a time gazetteer and to add spatial and temporal queries. We will also check whether our approach scales up to complete databases rather than just sculpture data. Another interesting area would be reasoning over the data in the triplestore. A simple application would be outlier detection in the data, including incorrect data that can only be detected by combining information from the different data sources.

In the user interface we are experimenting with the visualization of the results to present the possibilities to the archaeologist in a more user-friendly and intuitive way.

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Mieko Matsumoto and Espen Uleberg (eds) 2018. *CAA2016: Oceans of Data*
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Formalization and Reuse of Methodological Knowledge on Archaeology across European Organizations

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Abstract

Archaeological projects vary greatly in size, object of study, timescale and other aspects. Finding the most suitable methodology is often difficult, and an inadequate choice can ruin many months' worth of fieldwork and interpretation. An archaeological methodology should be as adjusted as possible to the project needs, consider knowledge that was successfully applied in the past, and be clearly expressed for better understanding and sharing. These goals are usually pursued informally through the application of tacit knowledge within archaeology organisations, leading to situations where it is difficult to convey what is expected to be done, methodological knowledge is underutilised and rarely reused, and the improvement of methodologies over time is difficult since no explicit knowledge about them exists. Some experiences exist with regard to using situational method engineering (SME) to mitigate these problems. In this paper we present the results of applying SME to the informal methodological knowledge of seven European archaeological organisations. Natural language processing techniques have been used to assist in this process. This work allowed us to obtain variations of established methodologies to cater for different project situations, combine different methodologies for collaborations and other hybrid scenarios, and reason about the methodological choices of different organisations.

Keywords: methodology, knowledge reuse, archaeological practice, situational method engineering, natural language processing

Introduction and motivation

Our work is motivated by realising three distinct but related facts about organisations working in archaeology. First, it is often difficult to convey what specialists are expected to do in specific situations, especially in relation to new team members or external collaborators. Guiding a large team in a complex project, especially when specialists from other disciplines (such as anthropologists or historians) are involved, is extremely time consuming and prone to errors. Secondly, methodological knowledge is underutilised and rarely reused, especially across organisations. In fact, many archaeological projects reinvent the wheel in terms of methodology, missing the opportunity to take advantage of previous experiences and existing expertise. Third, it is difficult to improve methodologies over time, since little explicit knowledge about them exists. This means that maladjustments and inadequacies in practices are rarely documented so that the next project can benefit from the acquired knowledge.

In this context, we need to define what we understand by *methodology*. Informally, a methodology describes how people do what they do. More specifically, a methodology is a systematic description of the processes that are followed, the products that are used and created, and the tools that are employed by a group of people to achieve a certain goal (Gonzalez-Perez and Hug, 2013). Long and tedious debates have taken place over the meaning of the term *method* in relation to methodologies. We acknowledge that usage varies from discipline to discipline but, for practical purposes, and in agreement with ISO/IEC 24744 (ISO/IEC, 2014), we will consider these two terms to be synonymous within this paper.

An archaeological methodology, to start with, must address the process to be followed. This is often expressed in terms of what tasks are carried out, what particular techniques are employed to achieve them, and how they are grouped into meaningful processes. For example, a task could be, 'determine extent of underground features'. Possible techniques to accomplish this could be *ditch surveying* or *ground-penetrating radar*, and this technique may be grouped with others into the process *site analysis*. These are just examples and we do not intend, at this stage, to propose a specific methodology organisation.

In addition, a methodology needs to describe what products are relevant. Process is necessarily performed on something, and for this reason the products that are created, modified or otherwise used by a methodology must be described. This is often done in terms of physical artefacts, documents, models, and other kinds of products. Some of them may be initially available and work as *inputs* to the methodology, such as the physical evidences on which archaeology usually relies. Some others are final or output products of the methodology, thus embodying its ultimate purpose, such as the new generated knowledge, or a particular report or consolidated artefact. Finally, some products are interim artefacts that do not pertain to the final results or the initial inputs, such as many datasets, photographs and documents. Products and process are intimately related, and a methodology must describe what tasks create, modify, or otherwise use what products, in order to obtain a consistent view of the dependencies that exist between process elements and products.

Finally, a methodology must describe the people, tools, teams and other producers, which are in charge of carrying out the process in order to create or use the products. Producers are often expressed in terms of the roles that people may play, in order to decouple the methodology from specific individuals, such as GIS Specialist or Excavation Director. Other producers are documented in terms of tools, such as Total Station or Database Management Software, or teams, such as Fieldwork Team or Lab Team.

Describing an archaeological methodology as outlined above constitutes a very analytical endeavour, and results in a collection of individual but inter-related 'atoms' that encapsulate methodological knowledge, such as how to perform a task or what a particular document kind consists of. This componentised information can be stored in a repository and made available to its users in a systematic manner, in order to assist with solving the issues described above. This is, precisely, what Situational Method Engineering (SME) has been proposing for other disciplines and, more recently, for archaeology too. The next section describes SME in depth.

Situational Method Engineering in archaeology

The comprehensive study and analysis of methodologies, regardless of their field of application, have been approached for the last couple of decades by the field of Situational Method Engineering (SME). Although SME was born as a discipline inside software engineering (Kumar and Welke, 1992; Rolland and Prakash, 1996), it has since been applied to a variety of fields, such as business process modelling (Gonzalez-Perez and Henderson-Sellers, 2010), archaeology (Gonzalez-Perez and Hug, 2013) and other areas of the humanities (Hug *et al.*, 2012). The fact that it is the word *method* (rather than *methodology*) that appears in situational method engineering obeys to historical reasons and, as we said in the previous section, we will consider *method* and *methodology* to be synonyms.

SME acknowledges that each methodology needs to be specifically situated, or adjusted to the project or endeavour to which it is going to be applied. At the same time, it tries to avoid circumstances that involve reinventing the wheel every time, by providing a solid knowledge reuse framework, so that methodologies are never created from scratch. In particular, and from the perspective of SME, a methodology is not a monolithic entity, but an assembly of *method components* that are carefully connected together after being selected from a pre-existing repository. Once a methodology has been created by assembling selected components, it can be enacted on an endeavour (i.e. applied to a project or other activity). During enactment, the performance of each component can be assessed, and the result of this evaluation fed back into the repository in the form of improvements to the components stored there. This way, methodologies that are assembled in the future from the improved components will take advantage from the accumulated enhancements that occur over time, thanks to the ongoing feedback loop. Figure 1 shows an overview of SME.

There are some aspects that must be clarified. Firstly, and as described in Gonzalez-Perez and Henderson-Sellers (2008a) and Gonzalez-Perez and Hug (2013), method components are reusable, atomic, self-contained packages of methodological knowledge, i.e. knowledge that is related to how things should be done, what artefacts are involved in doing them, who should do them, or similar methodological aspects. In this sense, method components encapsulate good practices, often distilled from accumulated experience and past errors. Different colours in Figure 1 are meant to depict different kinds of method components. Additional details on this are given below.

Secondly, and even though some of the method components in the repository change little over time, the specific ways in which method components are combined in order to make up methodologies are highly diverse, as are the ways in which said methodologies can be later enacted on specific endeavours. Method construction and method enactment, therefore, rely heavily on methodological requirements, which are often described in terms of what outcomes (such as documents, theoretical models or physical objects) the endeavour is aiming to achieve, the conditions of the environment where the endeavour will take place (such as any time or resource constraints that may exist), and the sociotechnical characteristics of the organisational environment (such as team management style or even

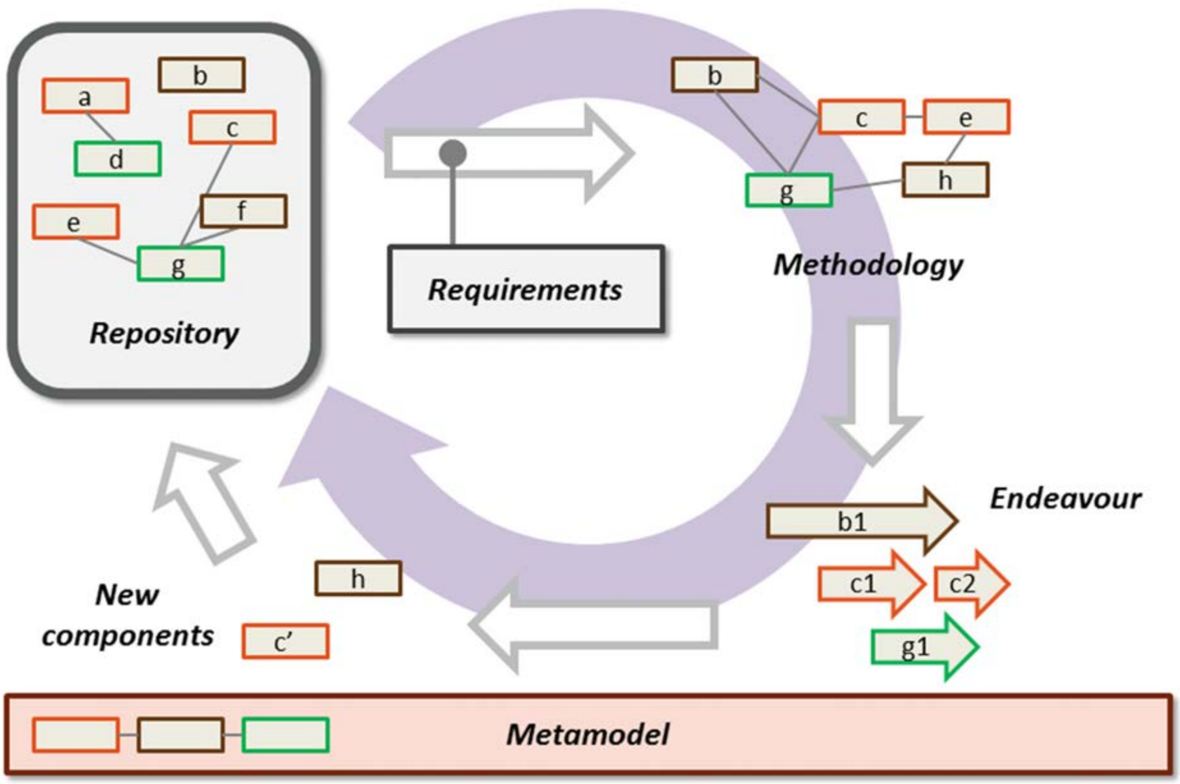

Figure 1. An overview of the dynamics of Situational Method Engineering (SME). The three major processes involved are depicted as boxes. Method components are depicted as small rectangles. The continuous improvement loop is depicted as a light circular arrow in the background.

personal preferences). Furthermore, by using SME, methodologies do not need to be frozen or static, but can be altered and adjusted, even during the course of a project, to cater for unexpected needs or respond to new information. This is accomplished through the incorporation or elimination of selected method components.

Thirdly, what types of method component are considered, and the ways in which method components can be assembled and enacted are regulated by a formalism called a *metamodel*. The metamodel acts as the grammar that dictates what kinds of combinations of method components are permissible, avoiding meaningless arrangements. The metamodel is not depicted in Figure 1, but it can be thought of as a set of operating rules that permeate everything that one does in SME, along the lines of the grammar rules that underpin a natural language when we use it to talk or write. Thus, having a solid and expressive metamodel is crucial for a successful application of SME. We have adopted the ISO/IEC 24744 (ISO/IEC, 2014) standard metamodel to this purpose. ISO/IEC 24744 implements, among others, the concepts that we describe above in the Introduction in the areas of process (through the WorkUnit class), products (through the WorkProduct class) and people (through the Producer class).

Finally, methodologies composed through SME should, ideally, be assessed for performance at solving the problems it is designed for, and taking into account the relevant methodological requirements. This is a quality-control issue that should be investigated from an empirical point of view and which, unfortunately, lies beyond the scope of this paper.

SME has been tentatively applied to archaeology and related areas on very few occasions. Hug *et al.* (2012) and Gonzalez-Perez and Hug (2013) are probably the only published attempts. The *Advanced Research Infrastructure for Archaeological Dataset Networking in Europe* (ARIADNE) project,[1] in addition, has adopted SME as one of the underlying technologies for methodological analysis and study.

Formalizing methodological knowledge

ARIADNE established the goal, among others, to understand how different technology-mediated archaeological practices are used across various European organisations. To this purpose, SME and the ISO/IEC 24744 metamodel were adopted. However, ISO/IEC 24744 has been designed for engineering-oriented

[1] http://www.ariadne-infrastructure.eu/

methodologies, and presented a number of minor shortcomings when applied to archaeology. To solve this, the standard metamodel was extended by using the built-in extension mechanisms. Then, descriptions in natural language were sought from project partners about their usual archaeological practices. The received documents were analysed by hand and through Natural Language Processing (NLP) techniques, thus obtaining the raw input for the SME repository. At the same time, an ISO/IEC 24744-compliant database was constructed to work as repository, and the obtained information stored into it. The following sections describe this work with more detail.

Metamodel extension

Our work uses an extended variant of ISO/IEC 24744. This extension involves three major innovations that are not part of the original standard. Firstly, the standard provides specific product kinds to describe documents and models, but this was not enough for archaeology. Two new classes were added under WorkProduct: CognitiveElement, to describe hypotheses, plans and other abstract ideas; and PhysicalObject, to describe physical objects such as a rock, a building or a piece of coal.

Secondly, two Boolean attributes were added to WorkProductKind in the standard, in order to describe the different availability situations of products. The IsExternallyAvailable attribute is used to document whether a product is readily available from external sources during a project (e.g. a public monuments registry), and the IsInternallyAvailable attribute indicates whether a product is internally available in a project (e.g. the team's accumulated experience).

Thirdly, we found out that methodologies are sometimes enacted in archaeology in a non-deterministic manner, so that the steps to take and the products to involve are not pre-established at the beginning of the project, but are defined 'on the fly' depending on interim project events. For example, unearthing an unexpected and large feature may mean that the excavation area is redefined and new staff is hired to cope with the extra work. In order to document situations like this, an association *Implies* was added from WorkProduct to WorkUnit, representing the fact that any particular work product (such as a redesigned work plan or altered hypothesis) that occurs during a project may imply a number of associated work units (such as new tasks or changed techniques).

Methodology reports

In order to gather information about archaeological practices, ARIADNE project partners were asked to document their usual practices in a concise and informal manner, by using plain English plus tables or figures. They were also asked to focus on the process that they followed (what tasks, activities or techniques they performed), the products that they engage (i.e. what documents, models, artefacts and other relevant things they used or created), and the people in charge of the former (i.e. what teams, roles or tools were employed). Eight partners provided reports describing archaeological practices related to 2D and 3D documentation of features and landscapes, site location analysis, recording during surveying and excavation, stratigraphic analysis, management and treatment of finds, analysis of various kinds of finds (stone, ceramic, wood, charcoal, phytolith, carpological, human anthropological, and archaeozoological), strontium and oxygen isotope analysis, archaeological impact management, and publication of archaeological results.

The reports were analysed, selected and processed by hand and also through NLP techniques.

Natural Language Processing

Given the potentially large number of methodology reports to be analysed, and the large amount of time that this consumes, we decided to apply some Natural Language Processing (NLP) techniques to aid with report analysis and method component extraction. Specifically, we selected unsupervised text mining with semantic analysis and no machine learning. A tool was developed in Python and using the Natural Language ToolKit (NLTK). The tool's final goal was to assist in the identification of methodological information from archaeological sources, so that method components could be easily constructed to be fed into the SME repository database. Previous collaborations with archaeologists (Epure *et al.*, 2015) and online resources (Council for British Archaeology, 2007) had revealed that the archaeological projects are driven by or operationalised through processes. An example is the excavation process, which consists of established activities, executed chronologically and satisfying various constraints such as two or more activities could take place in parallel, one activity depends on another, etc. All these processes followed during archaeological projects are explained in detail in textual reports, namely under a Methodology section. Consequently, these specific report sections become textual process traces.

Process Mining is the discipline emerging from Business and Information Systems whose goal is to discover processes from database logs (van der Aalst, 2011). The logs are structured traces of the human interaction with the software application. In our work (Epure *et al.*, 2015), an alternative to the traditional view of process

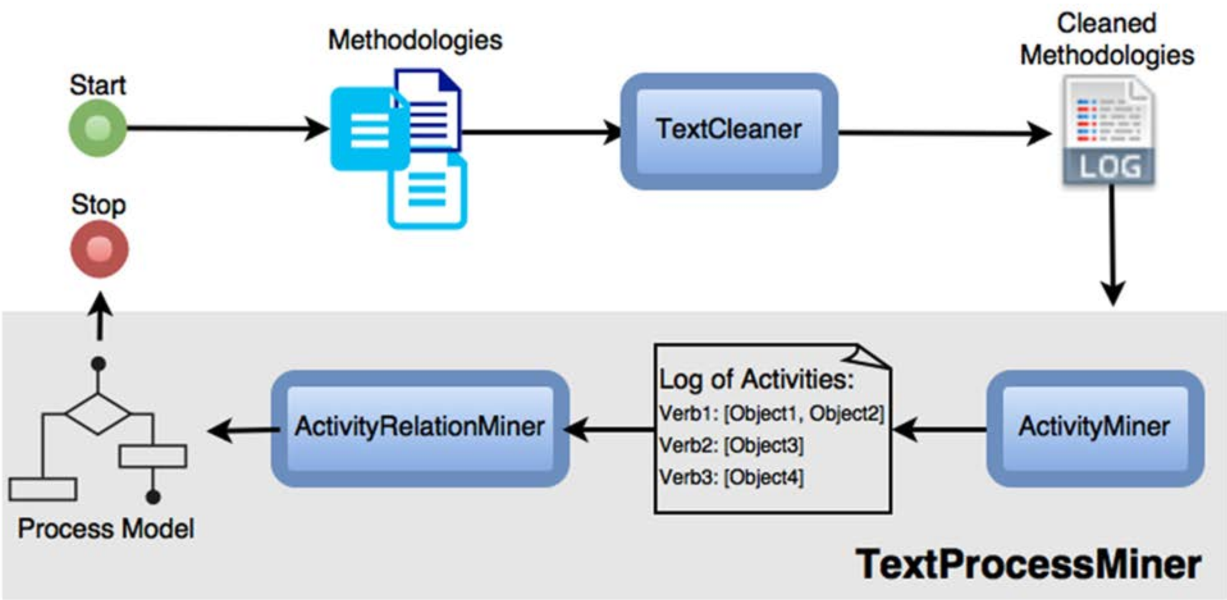

Figure 2. Overview of process mining as carried out for this work.

mining is proposed. Specifically, our solution handles unstructured, textual traces and has so far been applied to archaeology; a humanities domain where the process participants do not necessarily interact with the software for performing their activities.

Our solution, called TextProcessMiner, is presented in Figure 2. It consists of two sub-components: 1) ActivityMiner, which is responsible for the unsupervised discovery of process activities from text; 2) ActivityRelationMiner, which is responsible for the unsupervised discovery of the relations among activities from text, namely sequence, parallelism, mutual exclusion and decisions.

The input to TextProcessMiner is the cleaned methodology text previously produced by TextCleaner. No special requirements exist on this text, apart from it being Standard English. During this previous phase, the Methodology section is extracted from the document, its text is split in sentences, and several cleaning actions are performed: a space is introduced before and after punctuation signs, the comments in parentheses are removed if they do not contain verbs, and the sentences with negations are removed. These cleaning actions are necessary in order to standardise the textual format of the archaeological reports from different institutions, and all of them are easily automated.

Furthermore, the first component ActivityMiner discovers the activities from text. An activity is considered a pair formed by a verb plus its objects, such as "use toothless_bucket". The property of verbs to take direct objects is called transitivity. Thus, during this phase, the transitive verbs are discovered and their associated objects are identified. This is achieved by using natural processing algorithms for syntactically and semantically tagging the sentences, generating treebanks (Marcus *et al*., 1993) and word lemmatisation. Moreover, a knowledge base containing information about verbs and their transitivity was compiled from two external sources: VerbNet (Kipper *et al*., 2004) and WordNet (Miller, 1995). Both passive and active verb forms are handled. WordNet and VerbNet have a very broad coverage in relation to Standard English. The presence of very domain-specific terms from archaeology, which are not present in WordNet or VerbNet, however, may pose an obstacle, but this issue was not detected during the reported work.

Finally, the second component, ActivityRelationMiner, takes as input the list of activities produced in the previous phase and the original text, and outputs the process model, that is, the activities and their relations. The default relation is the sequence, because the activities are reported by default in the chronological order of their execution. However, if temporal markers such as 'before', 'after' or 'last year' are present, they are then considered for sentence re-ordering. The rule-based algorithm was built for identifying decisions, parallelism and mutual exclusion too.

The input to the rule-based algorithm is generated from the original sentence and its corresponding treebank accordingly: the tags of transitive verbs and other key structures as conjunctions, punctuation, and prepositions are kept; all the other content is replaced with '...'. For example, the sentence 'The excavations were structured to accommodate the requirements of the developer.' becomes '... 1.VBN to 2.VB ....'. Further, the algorithm takes each two consecutive verbs within a sentence and identifies their relation by applying a set of predefined rules. Notice that for the relation's identification, only the activity's verb is used. Several examples of rules are presented in Table 1. In the case that a verb has multiple objects enumerated with the conjunction 'and', then multiple parallel activities are extracted. Activities become mutually exclusive if the conjunction linking the objects is 'or'.

Rule input	Rule output	Explanation of symbols
... 1.VB/VBN/ VBD ... , ... 2.VBG ...	1 -> 2 (independent clause)	-> Sequence: activity 1 follows activity 2
... 1.VB/VBN/ VBD 2.VBG ...	1 || 2 (dependent clause)	|| Parallelism: activity 1 and 2 are executed partially or completely in parallel
... where VB/ VBD/VBN ... 2.VB/VBD/ VBD ...	1? -> 2 (decision)	? Decision: if activity 1 then 2 in sequence
... 1.VB/VBN/ VBD ... or ... in order to 2.VB ... , ... 3.VB/ VBN/VBD ...	1 x (2 -> 3) (branches)	x Mutual exclusion: either activity 1 or activity 2 followed by 3. () Precedence

Table 1. Some sample rules being applied to mine activity relationships.

The solution was validated in two steps: firstly, we performed an internal validation in a case study with the lead archaeologist of a project conducted in Villa Magna in Italy (Fentress, 2010). This case study validation was published as Epure *et al.* (2015) and allowed us to perform an initial evaluation of the solution performance. The solution was able to create the complete process model performed during the excavations of Villa Magna project with an 88% precision for activity recognition. This means that we were able to discover in an automatic way most of the methodological knowledge presented in the archaeological reports of Villa Magna. The final process model was validated by the lead archaeologist of the project and original author of the analysed report. The TextProcessMiner solution thus established a suitable basis to assist the identification of the reported methodological information in an automatic way.

Secondly, we used the TextProcessMiner solution to analyse multiple reports provided by four ARIADNE project[2] partners about their archaeological practices. These reports not only included information about excavation processes but also about other archaeological processes carried out within each institution, such as zooarchaeological analysis or 3D modelling methodologies. The results of applying the TextProcessMiner to these reports maintained the success rate in activity identification at over 80%, although additional problems with ActivityRelationMiner were found in relation to the identification of relationships between activities. We also noticed a greater presence of false positives in activities compared to the Villa Magna case. All of these aspects might be related to the great diversity of sources, archaeological practices reported, and authors of the reports. However, TextProcessMiner solution still allowed us to obtain initial process models for the four reporting institutions with no false negatives. This means that the solution identifies all the activities reported by the institutions involved without mistake and, in some cases, a few constructs that are not actual activities, which can easily be removed by hand. We can conclude that TextProcessMiner constitutes an effective tool for assisting archaeologists in the extraction of methodological knowledge embedded in reports. This information can be then fed into an SME repository as described in previous sections of this paper.

Nonetheless, improvements were also identified during both validation steps, including the naming of activities with anaphora resolution, the discovery of activities having transitive idioms, and the discovery of complex relations between activities. Also, we should remark that this approach is intended to support rather than replace specialist work, making it faster and easier for them; the intervention of an expert is still needed to validate the output of the tools.

Repository

As a final step, a database was created to work as SME repository by using Microsoft Access 2013 and the Microsoft Jet engine. The structure of this database implements the extended ISO/IEC 24744 metamodel, so method components of any of the necessary kinds could be stored and inter-related. The database was populated with the results from the manual and NLP-assisted processing of the methodology reports, resulting in over 220 individual method components plus multiple associations. Also, each method component is traced back to the source from where it has been 'mined'. Figure 3 shows an example of the contents in the repository.

Figure 3 is an action diagram for a proposed 'Total Station and GPS Georeferencing' process. The ellipses depict tasks that may be carried out as part of the process, whereas the rectangular shapes represent products that are used, created or changed. Each connection between a task and a product corresponds to an *action*, or event of usage. The letters inside the small circles indicate whether a particular task creates (C), reads (R) or modifies (M) a product. Note that no

[2] http://www.ariadne-infrastructure.eu/

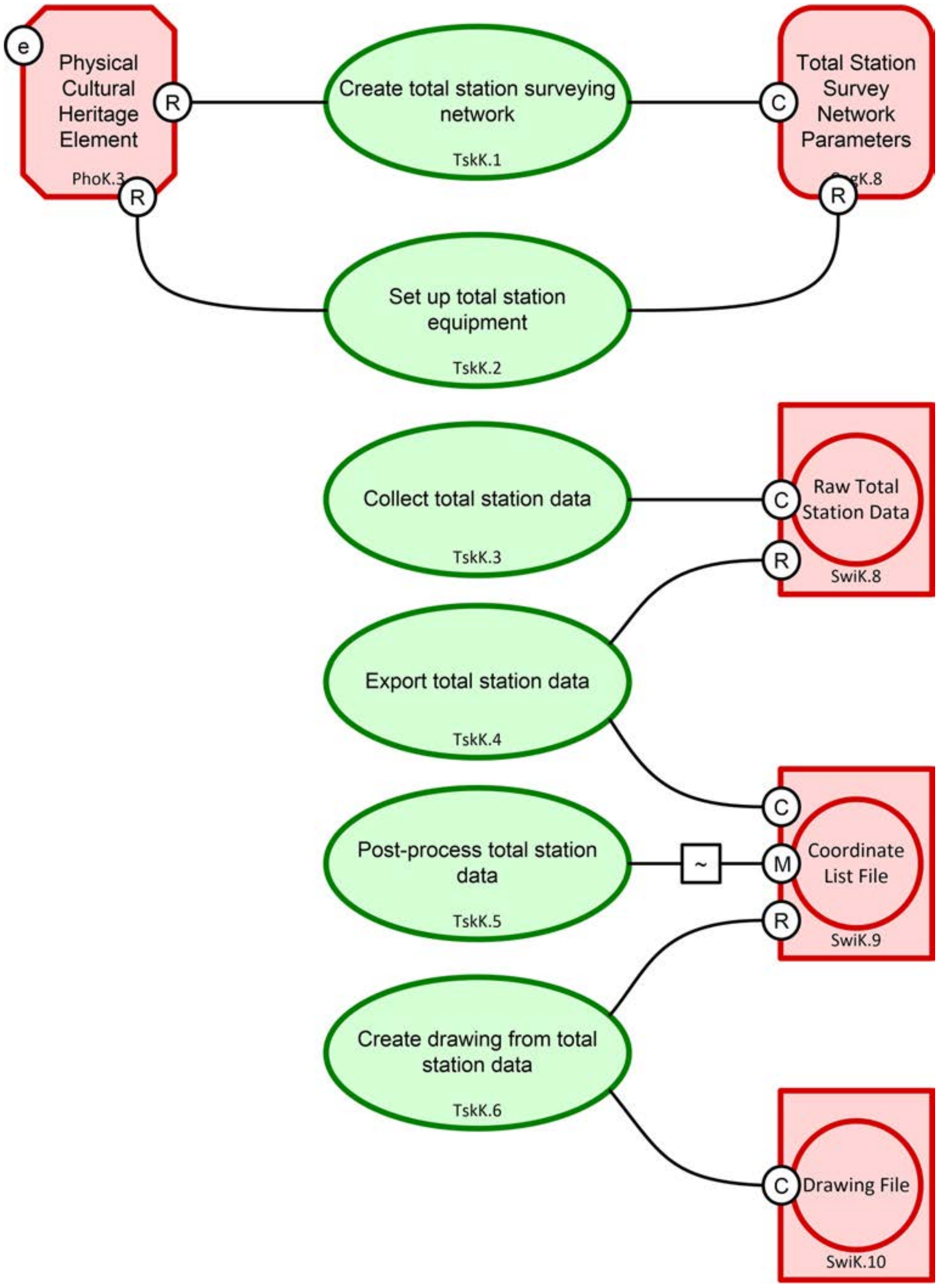

Figure 3. An action diagram for 'Total Station and GPS Georeferencing'. The ISO/IEC 24744 graphical notation is used.

explicit sequencing of tasks is given; in a project, tasks will be carried out as dictated by need and availability of the necessary products, producing in this manner an emergent sequence. For example, the 'Set up total station equipment' task needs to read the 'Total Station Survey Network Parameters' product, so usually this task may not take place before 'Create total station surveying network' has created it. This product-focused ad emergent approach has been previously described by Gonzalez-Perez and Henderson-Sellers (2008b).

Discussion of results

Having a repository of consolidated method components presents multiple benefits for archaeological teams concerned about methodology. The first situation under which benefits were observed was that of obtaining variations of established methodologies to cater for different project situations. For example, a paper-based survey process was easily transformed into a digital-based one by introducing a few new components and replacing the old ones while maintaining most of the process skeleton.

A second scenario under which the repository was very useful relates to the combination of different methodologies for collaboration or other hybrid scenarios. Often, a team working on a project externalises part of their process to collaborating partners. For example, an excavation team may rely on an independent laboratory to carry out radiocarbon dating or other specialist techniques. In situations like these, the methodologies of the client and the provider can be integrated into a continuous flow while maintaining their relative independence. This allows for either of the parties to alter their internal workings while maintaining the products at the boundary in order to keep the collaboration going.

A third scenario of utility for the repository was related to the dissemination and communication of the methodological choices of different organisations, as well as the reasoning about them. Specifically, having methodological knowledge discretised and arranged into a repository allowed us to describe specific portions of a methodology to any stakeholder in a precise and agile manner, deliver methodological knowledge to all the parties involved, and determine why specific products are being created or used, and detect those that are unnecessary.

Under these circumstances, methodologies become easier to convey to specialists, which is especially important in relation to new team members or collaborators of other disciplines. Also, methodological knowledge, being stored in the repository, is reused systematically every time that a particular component is chosen for a methodology. Finally, since components in the repository are constantly refined and adjusted, new methodologies benefit from the accumulated experience of previous users as they complete the cycle once again.

A few issues still remain. The analysis and processing of text-based methodology reports is extremely arduous, and although NLP tools help significantly, they still have to be augmented to detect work products and producers in addition to processes. Also, specialised tools are necessary for archaeological teams to browse the repository, compose their methodologies, and use them for a project. Without these tools, manual usage of repositories may be too cumbersome for some potential users.

Finally, research in SME tends to blur the distinction between two different but equally interesting goals: mining methodological knowledge out of expert organisations, and systematising said knowledge into digital platforms for its exploitation. In this paper, we have tackled both at the same time as a proof of concept, but future efforts may focus on one or the other.

Conclusions

In this paper we have proposed situational method engineering (SME) for archaeological methodologies, and described a particular experience involving the manual and NLP-assisted analysis and processing of a number of texts in order to construct a method component repository. This repository has shown to be useful in a number of scenarios, although the need for software tools makes its exploitation limited at this stage.

Nevertheless, the application of SME to archaeology looks promising, especially when aided by NLP tools that can help us 'mine' method components from textual sources. Still, reports may be highly heterogeneous, having a varying range of precision, quality and coverage. A characterisation of these aspects should be the focus of future research work.

Acknowledgment

The work described in this paper has been partially funded by the Advanced Research Infrastructure for Archaeological Dataset Networking in Europe (ARIADNE) project, FP7-INFRASTRUCTURES.

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Linked Open Data for Numismatic Library, Archive and Museum Integration

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Abstract
The American Numismatic Society (ANS), founded in 1858, is a research institute focusing coins from all eras and regions. It owns one of the largest collections of coins in the world, one of the largest numismatic libraries, is a publisher of monographs and journals, and maintains an archive of research notes from scholars associated with the Society. The Society's collection has been online since 1999, and it has been involved in various typological or hoard cataloguing projects that conform to Linked Open Data methodologies since 2011. These projects have been published at previous CAA conferences and in other venues, but the ANS is now undertaking the digitisation of its archival and library holdings. This paper will focus mainly on the integration of these materials into the ANS's existing data sets to form a cohesive research platform for numismatics that follows open standards and practices established by the broader Library, Archive, and Museum communities.

Keywords: semantic web, linked data, numismatics

ANS digital projects to date

The collection

The American Numismatic Society's collection comprises more than 700,000 monetary objects (coins, tokens, paper money, etc.) and organisationally similar non-monetary objects that are traditionally associated with the field of numismatics (medals, military decorations). These objects hail from all periods and cultures, but the collection is particularly strong in the Greek and Roman departments. As a result, most of our digital projects are related to these cultures. Digitisation of the collection began in the 1980s with the introduction of a DOS-based curatorial database. The database has gone through several migrations into its current form of FileMaker Pro. The web-based front end, available at http://numismatics.org/search, was first launched in 2011. Called MANTIS, this user interface is built on open source server applications and a middleware framework called Numishare,[1] which is the core application for most of the ANS's digital numismatic projects. FileMaker Pro data are exported as CSV and processed by a programming script into an XML schema, NUDS, which is the underlying data model Numishare is designed to publish. Today, nearly 600,000 objects are available in MANTIS, and more than 20% have been photographed.

Nomisma.org

Contemporaneous to the initial release of MANTIS was the development of Nomisma.org, an open access thesaurus of numismatic concepts that conforms to the principles of Linked Open Data (LOD). Many of the attributes by which coins are traditionally classified — denomination, material, and production places ('mints'), etc. — are reusable across many coins, which necessitates the publication of unique identifiers to define them. These identifiers are URIs, following LOD methodologies, where human- and machine-readable information may be accessed. The mint "Rome" is defined by http://nomisma.org/id/rome, and the Roman emperor Augustus, is defined by http://nomisma.org/id/augustus. A user may see a variety of information (maps, labels, matching URIs, example coins) by visiting one of these URIs in a browser, but the user may also request RDF conforming to a variety of serialisations via REST or HTTP content negotiation.

Initially a proof of concept created in 2010 by Andrew Meadows and Sebastian Heath, then both of the American Numismatic Society, Nomisma has grown into a widely recognised web service, guided by an international scientific committee of numismatists and information/computer scientists. Its usage in the cultural heritage sector has increased steadily over the years (Smith-Yoshimura, 2016). There is much to be said about Nomisma's evolution into the backbone for the future of numismatics, but these topics have been covered in various venues, both in terms of high-level vision (Gruber *et al.* 2013b, Meadows and Gruber, 2014) and low-level information architecture (Gruber, 2016) or mapping relational databases into RDF ontologies (Tolle and Wigg-Wolf, 2016).

It was apparent from the development of MANTIS that integration of Nomisma.org data would be vital to

[1] https://github.com/ewg118/numishare

drive controlled vocabulary for faceted browsing and geospatial mapping of mints. The NUDS XML schema was adapted to allow the linking of objects to URIs defining intellectual concepts published on Nomisma.org. Records in MANTIS may also link to URIs that define published typologies or coin hoards (often defined as three or more coins found in the same archaeological context). These databases are discussed below.

Coin typology databases

Coins have historically been categorised by a variety of individual attributes: the manufacture process, material, monetary denomination, mint, date, entities responsible for issuing the coin (whether individual rulers or corporate organisations), and the iconography and inscriptions (or 'legend' in numismatic terminology) on the front and back (obverse and reverse) of the coin. The combination of each of these individual attributes comprises a coin 'type,' and types are often uniquely numbered, thematically organised, and published in volumes of printed books.

For example, Roman Imperial coins have been published in numerous volumes over the last several centuries, but the standard reference work today is the ten volume Roman Imperial Coinage (RIC). Collections of Imperial coins therefore refer to standard type numbers from RIC, e.g. Augustus 1a, a silver denarius minted in Emerita (Spain) from 25–23 B.C. These numbers were once printed in collection inventories or cards associated with each coin, but are now inserted into bibliographic fields in museum databases.

In 2012, the ANS published the first edition of Online Coins of the Roman Empire (OCRE),[2] a digital type corpus based on the RIC numbering system. Following the patterns established by Nomisma.org, URIs were created for each RIC type number. RIC Augustus 1a is represented by http://numismatics.org/ocre/id/ric.1(2).aug.1A, where the 'ric.1(2)' in the ID sequence refers to RIC volume 1, second edition (Sutherland and Carson, 1984). OCRE was discussed in Gruber *et al.* (2013a), and while the functionality remains similar as it did in 2012, the architecture has evolved considerably to integrate more Semantic Web technologies, such as SPARQL.

The introduction of the Nomisma.org SPARQL endpoint in early 2013 facilitated a broader incorporation of materials from Nomisma partner institutions. The Berlin Münzkabinett was the first partner to make its Roman Imperial coins available in OCRE, following by large collections like the British Museum and smaller ones like The Fralin Museum at the University of Virginia. Coins have recently been incorporated from finds and archaeological databases, such as the UK's Portable Antiquities Scheme and OpenContext.org, managed by the University of California-Berkeley.

In 2015, the scope of online typologies was extended from Roman Imperial to Republican coinage with the release of Coinage of the Roman Republic Online CRRO[3] and PELLA,[4] the coinage issued in the name of Alexander the Great. The ANS is working to expand PELLA to include all Macedonian coinage, and will be publishing type corpora for the other Hellenistic kingdoms in the coming years. In total, about 15 partner institutions are contributing data for about 100,000 physical specimens associated with the type URIs published in OCRE, CRRO, and PELLA.

Coin hoard databases

The ANS's first online coin hoard project launched in 2013 as a collaboration with Kris Lockyear at University College London. This database, transformed from Lockyear's personal Microsoft Access research database into NUDS, was published in Numishare as Coin Hoards of the Roman Republic CHRR[5] (Gruber and Lockyear, 2015). Building on previous linked data work, CHRR extracts typological data from CRRO in real-time for display and analysis purposes. Each hoard is available at a URI, and these URIs have been incorporated into databases of Nomisma partner institutions, such as Berlin, which has made it possible to map find spots within their own collection.

In the Greek realm, the American Numismatic Society has published multiple print volumes of information and interpretation of coin hoards. An Inventory of Greek Coin Hoards (IGCH) (Thompson *et al.*, 1973) includes information for nearly 2400 Greek coin hoards, culled from publications, personal research notes, and other archival materials. Following IGCH, ten supplemental Coin Hoards volumes have been published. A prototype of the IGCH data is available at http://coinhoards.org, but much work remains to be done to make this project as robust as Coin Hoards of the Roman Republic. Nevertheless, the URIs published by this system are stable and have been incorporated into both MANTIS and the Berlin Münzkabinett, which has already opened the door to the direct linking between physical specimens, the typologies they represent, and the patterns of their geographic circulation.

The integration of these materials can be seen clearly at http://nomisma.org/id/tetradrachm, the URI that defines a Greek denomination. The map displays layers for

[2] http://numismatics.org/ocre/

[3] http://numismatics.org/crro/

[4] http://numismatics.org/pella/

[5] http://numismatics.org/chrr/

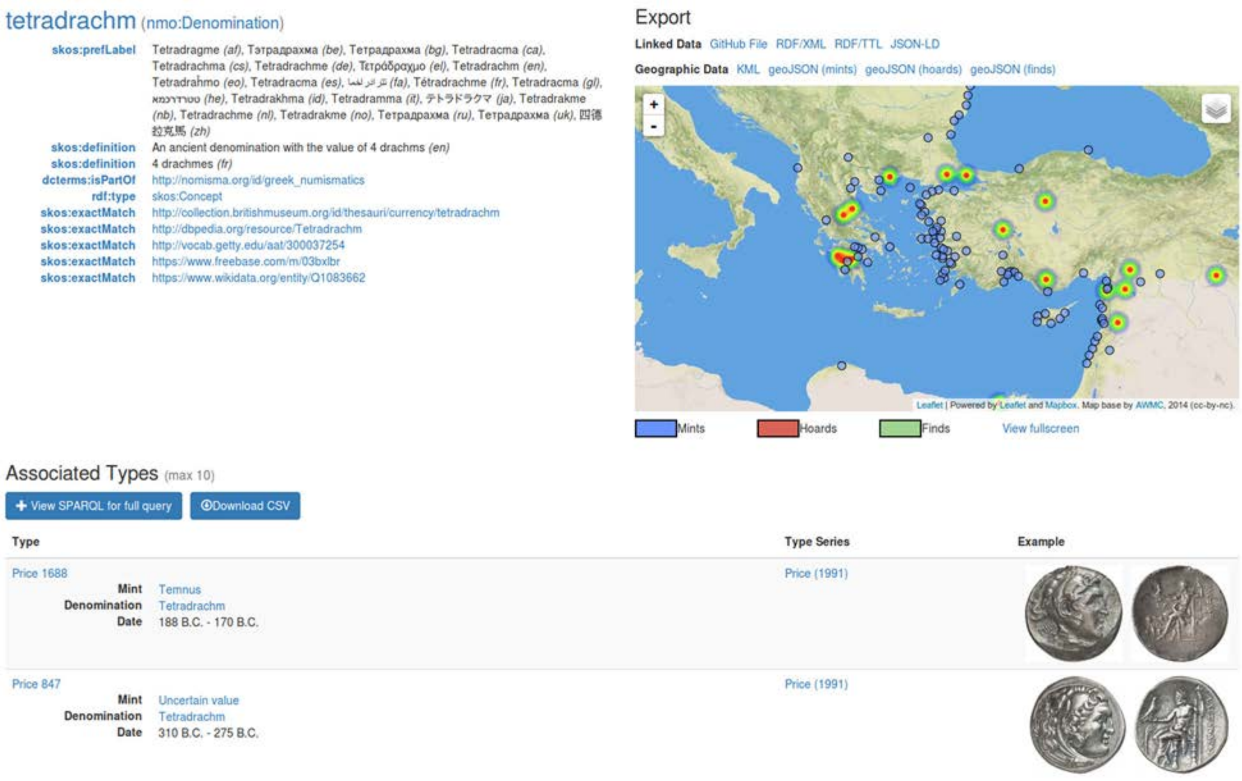

Figure 1. Screenshot of http://nomisma.org/id/tetradrachm.

the mints that produced tetradrachms (essentially a web service that transformations a SPARQL query into geoJSON, derived from types published in PELLA) and the places where they have been found (mainly derived from find spots in IGCH). Below the map are examples of related typologies, including photographs of coins of these types (Figure 1). The user may click on a hoard in the map to go to IGCH 1670,[6] and similarly, there are examples of coin types that have been found within this hoard, derived from MANTIS and Berlin. Additionally, there may be links to research notebooks or digitised monographs, as will be discussed below.

The archives

Shortly following the release of the first version of MANTIS in spring 2011 came the release of the American Numismatic Society digital archive, Archer.[7] In its first stage, Archer was an editing and publication framework for finding aids, which are documents that provide a description of the contents of an archival collection. This description may include the hierarchical organisation of the materials into boxes and folders, down to the level of an individual item. Finding aids were traditionally paper, but are now typically encoded in an XML standard called Encoded Archival Description (EAD). Archer is built on EADitor,[8] an open source middleware framework for the creation and publication of EAD finding aids. Architecturally similar to Numishare, EADitor was expanded to support the publication of other metadata standards common to the Library and Archives sectors, such as the Metadata Object Description Schema (MODS), a bibliographic model, and the Text Encoding Initiative (TEI), which is a mark-up language for textual transcription.

Like Numishare, EADitor has evolved considerably to be more LOD-aware, both in terms of web service lookup mechanisms (to link people to authority files published by the Virtual International Authority File (VIAF.org), link places to Geonames.org or the Pleiades Gazetteer of Ancient Places, and link genres/formats to the Getty Art and Architecture Thesaurus) and in the serialisation of EAD, MODS, and TEI into RDF to facilitate the interlinking between archival resources.

With a grant of $7,500 from the Gladys Krieble Delmas Foundation, in 2014 the ANS digitised 43 notebooks by prominent Greek numismatist and former ANS President, Edward T. Newell. This project entailed the generation of a Text Encoding Initiative (TEI) XML file for each notebook, containing bibliographic metadata extracted from the ANS's library catalogue DONUM and

[6] http://coinhoards.org/id/igch1670

[7] http://numismatics.org/archives

[8] https://github.com/ewg118/eaditor

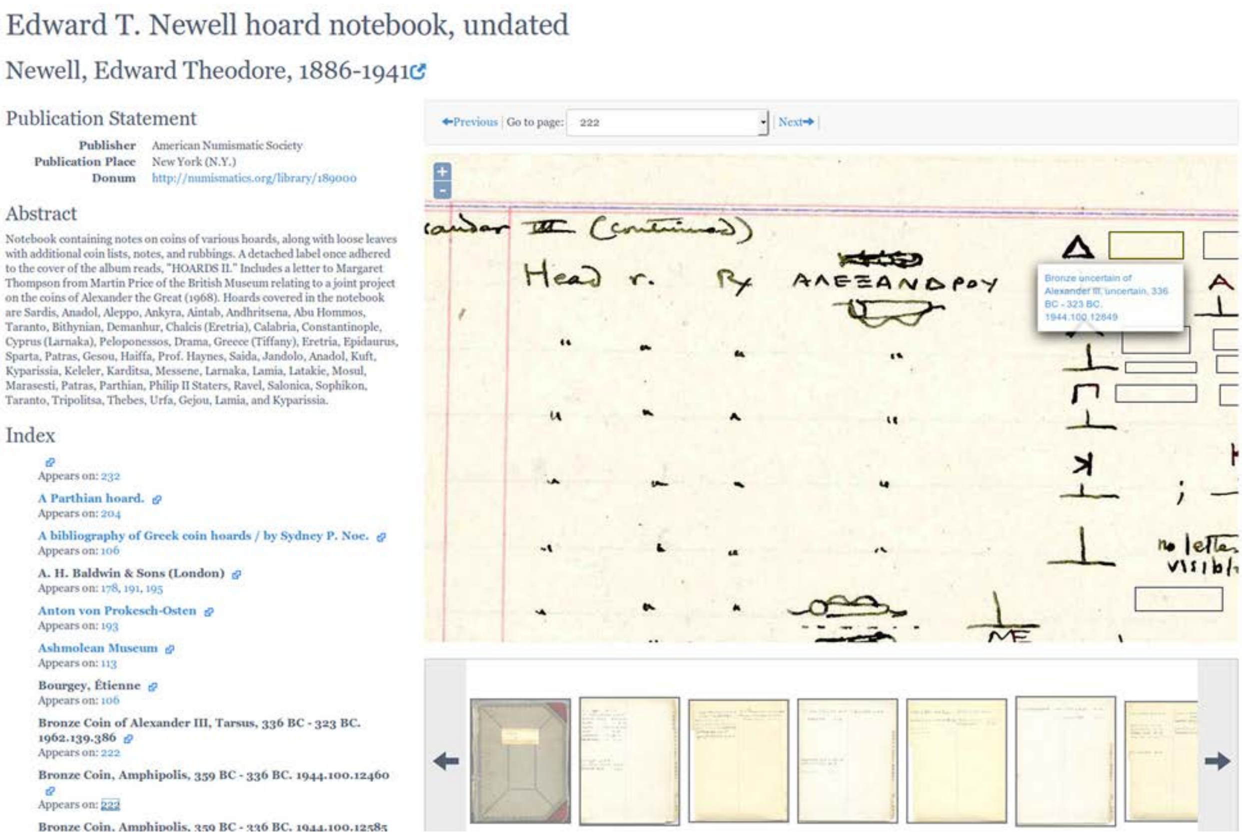

Figure 2. The user interface of an annotated notebook in EADitor.

a list of links to the scanned page images. By extending the functionality of EADitor to support TEI publication and image annotation with Annotorious,[9] Librarian David Hill and Assistant Archivist Arnold Tescher were able to rigorously annotate the coins, hoards, scholars, bibliographic publications, geographic places, and other sorts of LOD-defined entities in a handful of these notebooks (Figure 2). There remains much more work to be done to complete the annotation project.

A fundamental aspect of the ANS Archives is its personal and corporate authority system.[10] Publicly launched in 2014, the ANS Authorities section of Archer includes records for more than 100 people and corporate bodies associated with the Society. These include individuals that were members or officers of the Society or were prominent scholars in the field, for whom the ANS maintains archival materials (e.g. correspondences). These authority files are authored in another standard XML schema from the archival community, Encoded Archival Context — Persons, Corporate Bodies, Families (EAC-CPF), and published in the open source xEAC application,[11] which began development in 2012.

EADitor and xEAC both function as standalone applications, but can be configured to interoperate. That is to say, EADitor may interact with the Atom feed API published by xEAC in its EAD editing back-end to incorporate URIs minted by xEAC directly into finding aids. Both applications may be configured to interact with a SPARQL endpoint to create, update, and delete triples associated with archival authorities and materials. Therefore, a finding aid detailing the collection of Edward T. Newell[12] or a research notebook[13] will include the URI for Newell in the ANS Authorities system[14] as the creator (dcterms:creator). When publishing the EAC-CPF file in xEAC, the XML file will be transformed into RDF following a variety of ontologies relevant to biographical information and posted into the triplestore via the SPARQL/Update protocol. Likewise, EAD finding aids and TEI notebooks will be serialised into RDF conforming to Dublin Core Terms, Open Annotation, and other common ontologies and published from EADitor into the SPARQL endpoint. When one visits the URI for Edward Newell, that person may get a list of archival and library materials held by the ANS or other institutions. As a result, the page

[9] http://annotorious.github.io/

[10] http://numismatics.org/authorities/

[11] https://github.com/ewg118/xEAC

[12] http://numismatics.org/archives/ark:/53695/nnan0084

[13] http://numismatics.org/archives/ark:/53695/nnan187715

[14] http://numismatics.org/authority/newell

for Newell is more than a collection of biographical information and related people and organisations, but a gateway to more information by or about the scholar. In a few short clicks, a researcher might traverse the graph of numismatic information from Newell's biography to a notebook in the ANS archives to an IGCH hoard to a coin type in PELLA to a coin in MANTIS to the Nomisma.org URI for tetradrachm, which may include other, related research materials hosted by external services. The research potential is enormous, as scholars do not need to invest as much time acquiring information as before, and may devote more resources into the interpretation of evidence.

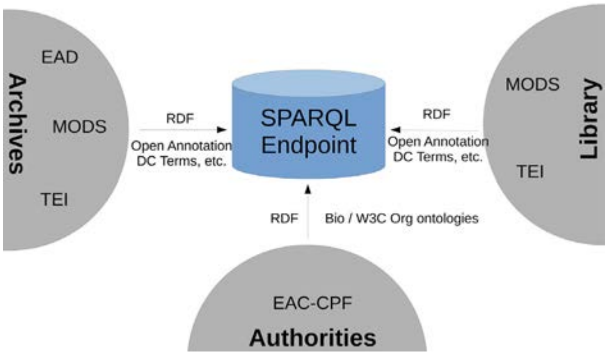

Figure 3. Interoperable models.

The Library

The American Numismatic Society maintains the largest collection of specialist numismatic literature in the world. Many patrons physically travel to the ANS office in New York City every year to conduct research, as many materials (like old auction catalogues or esoteric numismatic series) are very rare and generally inaccessible to the public. Among the materials in the ANS Library are series and monographs published by the Society itself. As it has demonstrated in other projects detailed in this paper, the ANS is fully committed to the free and open proliferation of knowledge, and it is striving to make its own out of print (but often, still in copyright) content openly accessible to the public.

As part of the Google Books project, roughly 500 monographs were scanned by Google's academic library partners. The scans of these monographs were transferred to HathiTrust for long-term sustainability, but only those published before 1923 are in the public domain. We have since issued a Creative Commons license for all works hosted by HathiTrust, making every one of them open. Building on this increased accessibility, the ANS applied for and received a grant for approximately $50,000 from the Mellon Foundation in December 2015 to transcribe about 80 of the rarest works into TEI, enhance with mark-up linking coins, hoards, entities, etc. mentioned in the books to URIs in our or other databases, and make these works available as EPUB 3.0.1 documents.

All of these monographs have been transcribed into TEI, but only a few are available online through the ANS Digital Library,[15] as of the date of this publication. The remaining will be completed by the end of 2016. The Digital Library is built on ETDPub,[16] which was initially conceived as a framework for publishing numismatic electronic theses and dissertations (including the full-text indexing of PDFs and LibreOffice/Word document files into Apache Solr). In early 2016, ETDPub was extended to support the publication of TEI and serialisation of TEI into EPUB, which is built upon the XML Pipeline Language inherent to Orbeon XForms' architecture. Like EADitor, monographs may be associated with URIs published in the ANS Biographies, and TEI files are transformed into RDF conforming to Open Annotation. As a result, researchers may access Coin Hoards[17] from the biography of Sidney Noe,[18] which will provide access to the Saida Find (IGCH 1508).[19] This hoard includes a reference to a specific page in one of Newell's research notebooks as well as points back to the section in Noe's book about the hoard.

What once began simply as an online database of the ANS's numismatic collection has evolved into a suite of purpose-built tools for publishing coins, types, hoards, archives, and library holdings, which are becoming increasingly interlinked — not just internally with respect to the Society's materials — but also paving the way these materials to be made available for scholars through other external services.

The underlying architecture

Application stack

From the above section, one may surmise that ANS digital projects follow a similar architectural pattern, which is mainly a product of the author's software development experience gained from the academic library realm, which is highly dependent upon XML technology. Numishare and EADitor were both borne from the Scholars' Lab at the University of Virginia between ca 2008–2010. These frameworks have advanced in a myriad of ways over the last several years, but three open source Java-based server applications remain fundamental aspects of the architecture of each

[15] http://numismatics.org/digitallibrary/

[16] https://github.com/AmericanNumismaticSociety/etdpub

[17] http://numismatics.org/digitallibrary/ark:/53695/nnan146115

[18] http://numismatics.org/authority/noe

[19] http://coinhoards.org/id/igch1508

framework. ETDPub and xEAC are built on this stack, and are designed to handle the creation, management, and publication of other types of documents. The server applications, which run in Apache Tomcat, are as follows:

Apache Solr:[20] Enables full text searching and faceted browse

eXist XML database:[21] Since many of the models that form the basis of the ANS digital collection, archives, and library are XML schemas, we use the eXist XML database. The eXist database supports XQuery, a query language for XML, which is used for back-end search and publication functionality, as well as for some APIs in Numishare.

Orbeon XForms:[22] The public user interfaces of these projects are driven by the Orbeon XML Pipeline Language (XPL), a data pipeline system for implementing Model-View-Controller (MVC) architecture in an XML framework. These pipelines enable the transformation of various XML or JSON data models (whether Solr search results, XML documents in eXist, SPARQL responses, or external REST services) into a wide variety of serialisations, from HTML for use in browsers to geoJSON or KML for geographic visualizations to linked data in the form of RDF /XML, Turtle, and JSON-LD. The back-end of these applications is driven by XForms, a W3C specification for advanced web form and data processing functionality.

Apache Fuseki:[23] A triplestore and SPARQL endpoint produced by the Jena project. It was chosen over other endpoints for its ease of use and excellent documentation. First tested in December 2012, it was placed into production in spring 2013 when OCRE was reengineered to interact with data aggregated with Nomisma.org's SPARQL endpoint. A second Fuseki triplestore is hosted by numismatics.org for aggregating library and archival linked data. Any SPARQL 1.1 compliant endpoint may be deployed in this application stack.

The development of these projects has been gradual over the last five years, with new functionality and enhanced interoperability introduced in iterative phases. MANTIS, which was once a data silo, became more incorporated with the broader Linked Open Data cloud through the integration of URIs published by Nomisma.org. With the launch of coin typology and coin hoard projects from 2013–2015, each project became more interactive, with data constantly flowing from one project to another. Nomisma itself is the keystone for the future of the discipline. The aggregation of physical specimens related to typologies, the metrical analyses of weights and diameters as part of the OCRE, CRRO, and PELLA interfaces, and the wide variety of geographic visualizations are all driven by the SPARQL endpoint hosted by Nomisma.org. SPARQL queries are so intertwined into the many user interfaces of these projects that the advanced Semantic Web information system underneath is invisible.

Much like MANTIS, Archer once was a silo of archival material — primarily EAD finding aids — that became increasingly interlinked with external authority systems like VIAF, the Library of Congress Subject Headings, and the Getty vocabularies. With the introduction of the ANS Authorities project, Semantic Web technology opened the door to linking between our own archival materials with internally-managed personal and corporate authorities. Even still, this integrated archives/authority system formed a kind of silo in its own right. The deployment of the ANS Digital Library extended the scope of our triplestore, enabling the linking between archival materials, digitised books, and our archival authority system.

The information about coin types, hoards, and physical specimens hosted by museum or archaeological database systems forms a powerful numismatic data ecosystem, but these databases form only a portion of the total human knowledge base regarding the study of coins. The ANS Library and Archives are another portion of this knowledge base, and much effort has been placed at the American Numismatic Society over the last year to better integrate the numismatic data ecosystem with the numismatic document ecosystem into a cohesive research platform. The publication of Edward Newell's research notebooks and electronic monographs as part of the NEH/Mellon Humanities Open Book Program have been instrumental in developing and testing a more thorough integration of these data and documents, as these documents include references to coins in the ANS and other collections as well as types and hoards published in digital catalogues like OCRE and IGCH.

Semantic web technology for complete LAM integration

The data models and software architecture underlying the ANS and Nomisma.org numismatic data ecosystem have been well published, even as recently as the 2016 CAA conference in Oslo (Tolle *et al.*, 2018) and XML London (Gruber, 2016), but it is nevertheless useful to briefly outline how this system presently functions.

[20] http://lucene.apache.org/solr/

[21] http://exist-db.org

[22] http://www.orbeon.com

[23] https://jena.apache.org/documentation/serving_data/

As mentioned above, the ANS digital projects published in Numishare are encoded in NUDS/XML. An RDF export feature is inherent to Numishare's functionality; essentially it is a workflow that executes XQuery to aggregate NUDS in the eXist database to pipe through XSLT into RDF. This RDF conforms to the Nomisma ontology,[24] but also incorporates other common ontologies such as Dublin Core Terms, Friend of a Friend (FOAF), and others. The precise model varies based upon the class of data object. Documentation for contributing data to Nomisma is available at http://nomisma.org/documentation/contribute.

RDF for physical specimens from MANTIS and partner institutions like the Portable Antiquities Scheme and Berlin Münzkabinett, as well as hoard projects like CHRR, link to type URIs published by OCRE, CRRO, and PELLA. The coin type RDF links to URIs published by Nomisma. All of these data sets are aggregated into a central SPARQL endpoint, enabling semantic reasoning across coins and hoards. A physical coin does not need to be explicitly designated as a 'denarius' when it links to a coin type that contains the property nmo:hasDenomination (in the Nomisma ontology) that links to http://nomisma.org/id/denarius.

Nomisma itself hosts a number of APIs that are queried by Numishare, such as 'Average Weight', which delivers a numerical response to a short-hand SPARQL query executed with request parameters (e.g. the average weight of denarii of Augustus from AD 10–15). Other more complex queries (for geographic visualization, for example) are executed directly in Numishare's XPL models and transformed through XSLT into KML or JSON for display by open source Javascript mapping libraries, like OpenLayers or Leaflet.

The document ecosystem of the American Numismatic Society is fairly similar to that of the numismatic data system, since the implementation of the EADitor–xEAC interactivity functionality was influenced by the lessons learned in the development of Nomisma.org and the aggregation of numismatic content. The difference with the implementation of Linked Open Data methodologies to archival materials is that there are no true standards for representing archival collections as a graph of information. Experiments in mapping archival collections to CIDOC-CRM have been conducted (Hennicke, 2013, Halling, 2016), but particular models of the CRM may vary from institution to institution. There is no one way to model anything in CIDOC-CRM, nor, arguably, should there be. EAD, like TEI, is a document model, and it is simply impossible to map all content from a document model into a graph. This is not the intention of linked data. However, digital books and archival collections may be represented as a graph in those areas that pertain specifically to linking web resources together: a) metadata (authors, genres, subject headings, dates of publication, etc.), and b) aspects of the body of the document that may be linked to other information systems.

For lack of a purpose-built archival Conceptual Reference Model, we chose to map document metadata (for electronic monographs, archival notebooks, finding aids, and other archival materials) to existing, commonly used ontologies on the web, such as Dublin Core Terms. We implemented Open Annotation for linking resources mentioned in sections of the body of a document. Furthermore, we used Dublin Core Terms to hierarchically link the components of documents together: sections and chapters in TEI files and series, sub-series, folders, and items in EAD finding aids. This would allow users to navigate from an object in MANTIS to the lowest level section of an EBook published in our Digital Library[25] or directly to the page of one of Newell's annotated notebooks.[26] The RDF from our library, archives, and authority system are aggregated into a single SPARQL endpoint, which can be queried by the ANS Authorities project, MANTIS, IGCH, or any external system. After years of development, we are now able to begin connecting our numismatic data and document systems together to form a comprehensive research platform, a suite of tools that will continue to grow in its usefulness as more data and documents are incorporated into the system. Linked Open Data principles are the foundation for this system.

Conclusion and future work

We have clearly demonstrated the potential for Linked Open Data methodologies to enhance access to numismatic materials as well as bind these materials more seamlessly together into a sophisticated research framework that incorporates museum and archaeological collections, hoard information, typologies, archival research materials, and digitised auction catalogues, journals, and monographs. Tens of thousands of Greco-Roman typologies have been published online, along with thousands of hoards, and data for 100,000 physical specimens have been aggregated, interlinked with these hoards and typologies. Within the next year, nearly 100 rare and out-of-print monographs will be openly accessible, annotated with references to coins, types, hoards, and a wide variety of other resources. So while there are currently a relatively small handful of examples of objects in the ANS numismatic collection link to books and archival materials, there will be a significant

[24] http://nomisma.org/ontology

[25] see http://numismatics.org/collection/0000.999.20456, for example

[26] http://numismatics.org/collection/1944.100.12599

increase in interlinked content within the next few years as the Humanities Open Book Program and the Newell annotation projects draw to a close.

Nomisma.org is central to the success of these projects. One of Nomisma's greatest advantages is the effort placed by the scientific committee in co-referencing between Nomisma URIs in concepts in other authority systems. One of these is the Pleiades Gazetteer of Ancient Places. By annotating mints and regions mentioned in our textual materials with Nomisma URIs, we are able to expose content to Pelagios Commons. Already, several ebooks are accessible in Peripleo,[27] making them available to researchers interested in ancient geography. We anticipate that other external aggregation projects will arise, and we hope that we might be able to make our material more broadly accessible to researchers who might otherwise not be aware of our content. Serendipity in research is one of the great potentials in developing large-scale Linked Open Data systems within the Library, Archive, and Museum communities.

Many different communities within cultural heritage and academics are working diligently to interlink their own disciplines, while simultaneously working to bridge gaps between fields. We are confident that in the coming decades, the numismatic research ecosystem will become more interwoven into the fabric of human knowledge.

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[27] http://pelagios.org/peripleo/map

Mieko Matsumoto and Espen Uleberg (eds) 2018. *CAA2016: Oceans of Data*
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
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Sustainability = Separation: Keeping Database Structure, Domain Structure and Interface Separate

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Abstract
Relational databases normally model the knowledge domain directly as database structure: tables represent entities and their relationships; forms represent views dependent on specific joins; workflows and interfaces are customised through programming. This approach is inherently unsustainable due to the embedding of essential semantics in custom programming and dependence on specific software/versions; the data cannot exist without the program.
In this paper I discuss the use of meta-structures representing the knowledge domain as user-modifiable data within the database, allowing a fixed, well-documented format across all applications. This promotes sustainability, since the only requirement is a database which can manage SQL tables, and standard SQL queries retrieve the knowledge domain structure and content.
The paper also argues that the user-interface — often confused with the database itself — is merely an end-user convenience and should be regarded as transitory and replaceable; it is not part of the data sustainability equation.

Keywords: databases, database modeling, meta-structures, software independence, sustainability

From spreadsheets to relational databases

As a discipline we have a history of borrowing and adapting methods and tools from other domains. The widespread adoption of spreadsheets and relational databases in Archaeology is due to a number of factors including the nature and scale of archaeological data (broadly compatible with a spreadsheet or table view) and the long history (since the 1960s) of computerisation of field and analysis data within the discipline.

Much of the early computerisation of data in archaeology, through the 1960s and 1970s, took the form of flat-file tables formatted for analysis by statistics packages such as SPSS (e.g. several examples in Gaines, 1981). Spreadsheets, when they blossomed in the 1980s (Lotus 123 from 1983, Excel from 1985) as one of the early 'office' applications associated with the rise of personal computers, were a natural fit for these data. Spreadsheets were initially developed, as implied by their name,[1] to manipulate columns of numerical data with simple text labels, such as those found in accounting. Their use expanded rapidly across a broad range of applications, from administrative lists to scientific data, as people found that their zero entry threshold — just start typing data in cells whose type could be determined after-the-fact — and increasing ability to apply formulae and create graphs, allowed individuals and projects with limited resources to create, edit and manipulate their own data without the cost, delays and dependency associated with mainframe systems. Archaeology, as a discipline with a desperate need for better methods of recording and manipulating relatively small amounts of data (in the hundreds or thousands of records[2]), siloed in separate files of different specialists (although often with common references e.g. excavation trench, square, layer and unit number), was a prime culture for a simple tool of this type. However, despite their utility at the individual level, spreadsheets discourage modelling of related entities and encourage the creation of file-based data silos, as there is no robust mechanism for linking data across separate spreadsheet files. As a result, they tend to discourage good, integrative data management practices.

While spreadsheets filled — and continue to fill — an immediate need in a siloed environment, it quickly becomes apparent that most projects need better integration of specialist data, along with better control and richer data entry through forms, validated fields, lookups, broader data types e.g. images and long texts, and access control. The availability in the 1980s of early relational databases such as dBase II, with a relatively modest entry barrier and a programming environment within the reach of the adventurous amateur, led to a proliferation of custom applications in which the programming was tightly linked to the structure of

[1] The term 'spreadsheet' refers to the sheets used by accountants to record transactions.

[2] Referred to as 'cases' in statistical packages and 'rows' in spreadsheets.

the database. At a time when the idea of linking data across projects was no more than a glimmer — indeed the prevailing concept was monolithic, as implied by the title of Gaines (1981) seminal volume "*Databank Applications in Archaeology*" — this did not seem like too much of a problem, although my work on the end-user configurable *MINARK* database system (Johnson, 1984) was partly a response to the redundancy of effort and incompatibility of custom database development.

The spread of custom relational databases was further encouraged by the increasing availability from the mid-1980s of easily customised 'office' databases such as FileMaker (1985) and later Microsoft Access (1991), which embedded the database inside a user interface environment (so successfully that most users of Access were, and probably still are, unaware that the database could be directly manipulated with SQL). Such tight integration of database and program tends to lock data into a particular system and further encourages custom applications; by hiding the complexity of the underlying structure and providing wizards and drag-and-drop programming, end-users with little understanding of the relational approach are encouraged to roll their own without regard to wider use.

More recently, the rise of the web and widespread availability of SQL server databases such as MySQL, Postgres, MSSQL and Oracle, and the explosion in tools for generating and enriching web pages, has encouraged professionalization of database development, with dedicated staff and/or trained programmers involved in the development of complex web-accessible relational database applications. Modern examples include flexible reusable systems built on a relational DBMS base, such as Intrasis,[3] IADB,[4] ARK,[5] FAIMS[6] or Heurist[7] and complex site databases such as the one developed for Çatalhöyük.[8] Even with the rise of new database methodologies — including NoSQL databases, object databases, graph databases and triple stores — relational databases remain foundational in many archaeological projects; the Çatalhöyük database is a case in point, where an underlying relational database generates the 'Çatalhöyük Living Archive', including linked data delivered through an RDF triplestore and SPARQL endpoint.

Rationale for meta-structure

As noted above, spreadsheets have a very low entry barrier and can be efficient for handling structurally simple and repeatable datasets, such as specialist analyses involving samples, quantification and graphical display. However, when turned towards heterogeneous collections which should be modelled as separate entities and relationships, they have encouraged unspeakable crimes against good data modelling. Such spreadsheet 'databases' may end up a spaghetti soup of multiple entity types per sheet, multiple entities per row, rampant redundancy, uncontrolled coding, multiple values per cell, positional significance, and cells blown out with discursive text. They are often a response to the mismatch between the data modelling required and the expertise and/or technical resources available.

The conventional approach to designing SQL databases, on the other hand, is to tightly couple the structure with the specifics of the data to be recorded. Tables typically reflect the entities modelled, the relationships between these entities, lookups for controlled values and multi-value fields; the interface software is built to manage those structures. Consequently, this approach to managing data tends to generate problem-specific databases which are tightly tied to a particular method of recording. The structure itself carries much of the semantic payload, which may also be embedded in locally programmed forms, triggers and functions. While there are plenty of tools for streamlining development, from database wizards to UML and frameworks, this approach to database design is ultimately a project-specific programming approach, with limited portability across projects, and often locked into a particular DBMS (and even to a specific software version).

Such custom databases typically grow with a project in response to specific needs, are often constrained by resources (specifically the availability of qualified technical personnel), and are often partial and *ad hoc*. They are cheap to start with, but costs escalate as requirements evolve and the project becomes more dependent on them. They may evolve into a more generic system as other projects start to adopt the same methodology — such systems are often embedded in a particular tradition of field recording. However, there is a danger that the specialised structure of an evolved custom system will start to straight-jacket projects by imposing a particular way of thinking about the entities involved, their relationships and what one can do with them, as well as making change too costly and/or difficult to contemplate.

Meta-structure databases

In the mid-1990s, Jens Andressen and Torsten Madsen at Aarhus University developed an elegant model for their IDEA database system (Andresen and Madsen, 1996; later generalised as GUARD, Madsen, 2001b;

[3] intrasis.com
[4] iadb.york.uk
[5] ark.lparchaeology.com
[6] FedArch.org
[7] HeuristNetwork.org
[8] catalhoyuk.stanford.edu

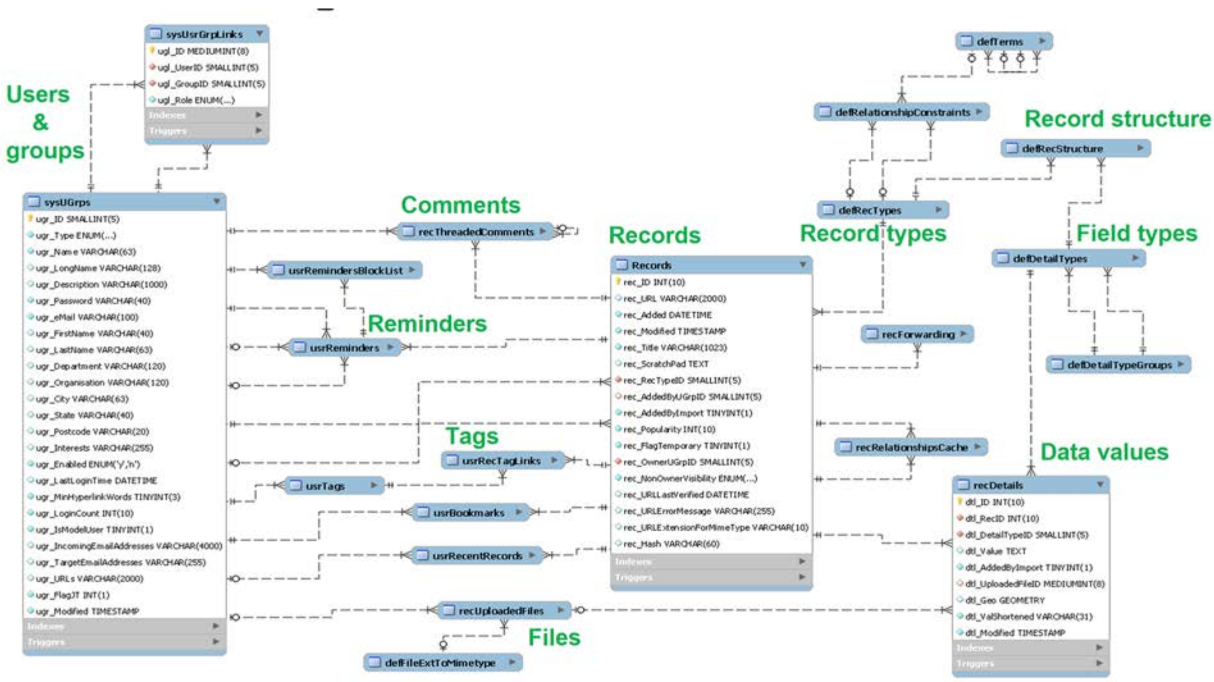

Figure 1. Heurist database structure (simplified).

and ArchaeoInfo, Madsen, 2003), which reduced the archaeological excavation domain to just three main tables — 1. **objects**, 2. **deposits** and 3. **constructs** — which could then be adapted to a wide range of different recording systems. The system was built on MS Access, because it was '... a Relational Database Management System (RDBMS), **naturally**' [my emphasis].

A decade later (2005) I started designing Heurist[9] based on the MySQL server DBMS, using an even simpler database construct (Figure 1) consisting of just two main tables[10] — 1. **Entities/records** (providing a unique identifier for each entity and defining ownership and access), and 2. **Attributes/Data values** (represented as key-value pairs linked to an entity by a foreign key). These tables are agnostic as to the nature of the entities recorded, notably treating relationships between entities as first-order entities in their own right. As a result, Heurist is no longer specifically archaeological but can be adapted to a much wider range of applications. The majority of current applications are historical rather than archaeological, including public websites such as the Dictionary of Sydney,[11] Bali Paintings,[12] and Digital Harlem[13] (Robertson, 2013).

A further decade later, 2014, the Field Acquired Information Management System project (FAIMS; FedArch.org) developed a generic database structure in SQLite for their Android field data collection app which uses a very similar structure — entities and attributes — with similar supporting tables (although relationships are handled as a special type of entity with their own entity and attribute tables). Like Heurist, this system has rapidly found application beyond archaeology, notably in geochemical field recording. The Heurist and FAIMS systems are inter-operable to the degree that any Heurist database can be used to generate the database schema and configuration files for an equivalent FAIMS database and data collection app, and can reimport the schema and data from a FAIMS database.

The concept of using a relational database with fixed structure, in which the user's data model is defined by data and implemented through reusable program components, is by no means unique. These three systems are simply those with which I have had considerable personal involvement. Within archaeology, as within the broader field of Digital Humanities, we can find many more examples, such as Michigan State University's KORA digital repository[14] or the Omeka collection publishing system.[15]

Why meta-structures are useful

Already in 2001, Madsen noted several major advantages of what he called a meta-structure:

[9] HeuristNetwork.org
[10] As with IDEA, another ~40 tables manage the coding, content and access to these tables.
[11] DictionaryOfSydney.org
[12] BaliPaintings.org
[13] DigitalHarlem.org
[14] kora.matrix.msu.edu
[15] Omeka.org

> '... what creates the structure of a particular recording system is by itself data entered into the database at user level. The database becomes a meta-structure for recording systems, which means firstly you can design widely differing recording systems without changing the underlying database structure and secondly that you can adjust any particular structure at any time, as long as the changes do not interfere with data already recorded' (Madsen, 2001a, p. 7).

This stability of structure means that software components can be developed which operate on all databases and target recurrent database patterns (for example, multi-value fields or foreign key relationships), leading to significant economies of effort and cost through a develop-once, use-many times approach. Stability of structure also means that the structure can be documented once-and-for-all and reused many times, so that it becomes a well-known construct; practitioner skills then become transferable between projects.

By reducing the development of custom structures and applications on a per-project basis, this standardisation of structure is an important factor in data sustainability. Madsen puts it thus:

> 'One benefit of such a [meta-structure] database is that accessing data can always happen through the same application interface no matter what particular data structure is actually at hand, and it will thus be infinitely easier for users to access data. Furthermore, time could be invested in creating efficient and powerful ways of searching and presenting data, because the investment would not apply to just one database instance, but to all instances' (Madsen, 2001b, p. 101).

Madsen also notes:

> 'The meta-structure must be flexible (able to handle widely different recording structures), relational (in principle everything can relate to everything), dynamic (can adapt to changes in data structures as they are introduced), and have a memory (it should be possible to reconstruct the state of recordings at any point back in time. The aim of the meta-structure is to provide a sound basis for data recording ... and for the storage of these data for future use' (Madsen, 2001a, p. 2).

This emphasis on flexibility, and relationality plays well with archaeological data structures which are quite heterogeneous, richly interlinked, and often evolve due to the unpredictable nature of archaeological discovery. It also tends to counter the argument that digitisation, and specifically the use of standardised tools, locks projects into specific ways of thinking and reduces creativity, since the more open and flexible the system the less the user is constrained. Madsen perhaps implies, but does not state, that the meta-structure and tools should be Open Source.

A further reason for the use of meta-structure databases lies in the way that complex relational operations can be encapsulated as simple interface choices. It is not a trivial matter to model an archaeological project in a relational DBMS structure, let alone to implement it as a web-accessible database. In a modern meta-structure system the process is greatly simplified by implementing common database patterns as simple choices. For example, a multi-value lookup to multiple target entity types (tables in a relational system) — for instance, setting multiple authors of type Person *or* Organisation, and whose order must be maintained — is reduced in Heurist to defining a Record Pointer field, setting it as multi-value from a dropdown and selecting the target entity types from a list (value order maintenance is automatic).

Against these broadly positive attributes of virtualised databases or meta-structures, it is germane to point out that such systems will typically display rather more generic interfaces and may have slower response than custom systems developed on the same platforms, and this may make them harder to 'sell' to prospective users. For example, Heurist lays out all fields one above the other for simplicity, rather than mimicking a paper form with freeform layout (which can improve usability in skilled hands, but more commonly goes in the opposite direction). However, as Madsen observed (Madsen, 2001b, p. 101), the concentration of design effort on a single generic view can lead to greater usability than a one-off form constructed with inadequate planning, whilst well-designed generic interfaces can also be an advantage in allowing skills transfer across projects.

On the speed side, Moore's Law takes care of many speed and data volume issues at a pace exceeding growth in data volumes, although a meta-structure system may not be suitable for databases in the order of millions of records. In our experience, most project databases are in the range of tens or hundreds of thousands of records, and at this scale the speed of response is often a function of internet speed, with most queries processed on the server in less than a second and the most complex object network traverse running in under ten; smart indexing and caching on the server, and local javascript caching on the browser, ensure responsiveness of the user interface for actions such as dropdown lists. Databases with millions of records, on the other hand, are typically generated by automated systems (such as harvesting of social media or of multiple heritage registers), rather than by human data entry within a single project. Such very large database will often have quite simple structures which can be processed with straightforward scripts or queries, or will belong to large organisations which can afford the costs of custom development and maintenance.

The application is not the database

When considering sustainability, it is natural to ask the question 'how long will this system be maintained?' To do this for a meta-structure database, such as Heurist, is to confuse the underlying database with the interface, i.e. the software which is used to manipulate the database at any given time. While many relational DBMS applications inherently require both the code and the database in order to fully represent the content (this is particularly the case for desktop systems such as FileMaker or MS Access, and for most custom databases developed for a specific project), meta-structure databases draw a clear distinction. The term *Heurist*, for example, can refer to:

Database: A fixed MySQL database structure of 42 tables

> The MySQL database contains ALL the information required to represent the data. Coupled with a description of its structure and a series of documented SQL queries, which will work for any Heurist database, it is a complete representation independent of any specific software other than MySQL, and can be exported as a text-based SQL representation which could be loaded in any SQL server (with a little work). In the case of Heurist the database can also be exported as a fully self-documenting XML representation of the structure and data, along with embedded file resources in their original format.

Interface: Programs used to manipulate the MySQL database

> These are a **convenience** for usability, which at heart simply build (complex) SQL commands which could be issued directly at the SQL command line. They may consist of programs in multiple languages and/or programs which are alternative ways of doing the same thing. They are not an **essential** component for interpreting or manipulating the content, and need not therefore enter into the long-term sustainability equation (their absence can, of course, be quite inconvenient for a project in the short term).

Conclusion

Following the above discussion, I would argue that nearly all archaeological data systems should be based on a generic meta-structure approach, along the lines of the examples discussed in this paper, to ensure flexibility for change, long-term data sustainability and shared investment in infrastructure. Only where the specific characteristics of the problem can be shown not to be amenable to a meta-structure approach should project-specific database structures be developed (this might be the case for specialised data types such as 3D models or complex geospatial data, but should rarely apply to the entity, attribute and relationship-rich types of data characteristic of most archaeological projects).

However, I am sufficiently sanguine to believe that the majority of projects will either adopt domain-specific tools with constrained data models and behaviours, due to their availability and common use within a particular community, or continue to build custom data structures and tools, due to the difficulty of identifying suitable candidate systems within the information deluge (the DiRT directory, dirtdirectory.org, web searches and the literature may provide pointers, but generally fail to provide much guidance on selection). Practitioners will tend inevitably to plunge in and roll their own using immediately available or widely-known tools rather than researching potentially less-known but more appropriate solutions. Frustratingly, it is far harder to convey the value of a broadly-applicable, flexible solution than a narrowly-targeted, inflexible one.

Over the coming year our aim is to make Heurist more attractive to archaeological projects by building and publicising templates for different archaeological applications, embedding existing standard ontologies and creating exemplars. This may at first appear to be giving in to the pressure to develop domain-specific models and methods, but the nature of a meta-structure approach means that these are starting points rather than endpoints. On the software and sustainability front, we will be developing add-ons which better connect Heurist with external systems, including more seamless generation of RDF linked data, OAI harvesting and standards-based archive packages.

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Mieko Matsumoto and Espen Uleberg (eds) 2018. *CAA2016: Oceans of Data*
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
Oxford: Archaeopress

Systematic Literature Review on Automated Monument Detection: A Remote Investigation on Patterns within the Field of Automated Monument Detection

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Abstract

This study measures the state of automated procedures within cultural heritage detection and management by correlating key terms for remote sensing by citations. The availability of remotely sensed data has increased the demand for automated procedures that can handle large amounts of digital information for landscape analysis and monument detection. We analyse the evolution of the field, by conducting a systematic literature review using standardised search structures on publications related to automated monument detection. The review reveals general trends and connections between different fields, but does not indicate whether the patterns are based on collaboration, networks, inspiration, or autonomy. We then deploy network analysis to identify community structures based on internal impact measures, as well as external factors such as research methodology and location. The trends and patterns within the combined results of network analysis and systematic literature review allow for a critical assessment of current research practices, highlight emerging best practices and evolution of the field.

Keywords: Network Analysis, Systematic Literature Review, archaeological computing, automated detection, pattern analysis

Introduction

This study focuses on automated procedures for the detection of monuments in the landscape as part of archaeological mapping. After looking at the historical development of automated procedures and remotely sensed data within archaeology, we continue with a methodological discussion of Systematic Literature Review (SLR) and Network Analysis (NA). These processes provide the main target for our discussion and conclusion.

This work is a response to the increased availability of data from vast areas of diverse landscape shaped by the past and present. Especially with the availability of LiDAR data, digital landscape analysis and detection of cultural heritage monuments has developed rapidly during the last 15 years. Consequently, this increase in information has amplified the need for automated procedures for monitoring, surveying and detection of known and unknown monuments. Whenever tools and procedures, such as these, cross knowledge domains they invariably split existing disciplines into those familiar and engaging with the new, and those that don't. The pattern by which new knowledge is spreading, and where appropriation takes place, holds vital clues for understanding the long-term impact of the procedures in question. Remotely sensed data, from the mid-19th century and onwards, has shaped analysis, detection, and management of archaeological knowledge. It has evolved into a spearhead practice within the discipline. After the First World War, archaeologist used oblique images and orthophotos captured from low-flying airplanes for aerial reconnaissance and documentation (Cowley *et al.*, 2010; Olesen *et al.*, 2011). Remote documentation of crop marks, monuments, and landscapes remains the most common approach for large-scale archaeological reconnaissance and management (Cowley *et al.*, 2010; Olesen *et al.*, 2011; Olesen and Klinkby, 2012; Verhoeven, 2009). Satellite and aerial vertical images have similarly increased the documentation of past and present landscapes, either as supplementary information (e.g. De Laet *et al.*, 2007; Figorito and Tarantino, 2014; Hesse, 2015) or as the main documentation (e.g. Grøn *et al.* 2004; Lambers and Zingman, 2013; Siart *et al.*, 2008). Analysing crops and subsurface differentiation in hyperspectral images may provide unique proxy values for understanding in-situ cultural heritage in the landscape (Cavalli *et al.*, 2013; Custer *et al.*, 1986; Doneus *et al.*, 2014). With LiDAR data, another source of information for understanding landscapes is available (Opitz and Cowley, 2013). In the following, we look at the changes to the field of research in light of these developments.

Understanding cultural landscapes requires both data analysis and correlation with other sources of remotely sensed data. Yet, the individual procedures of comprehensive large-scale studies and repeated site management are time consuming. Due to the lack of public sensation value, and subsequent funding, such tasks tend to be neglected. (Semi-) computational automation of the repetitious tasks of processing large-scale remotely sensed data, such as: automated geo-referencing (e.g. Verhoeven *et al*., 2012), automated site detection (e.g. Menze and Ur, 2012; Trier and Zortea, 2012; Schneider *et al*., 2015), and machine learning towards automatic analysis and feature learning (e.g. Arel *et al*., 2010; Belgiu *et al*., 2014; van der Maaten *et al*., 2007; Trier *et al*., 2016) are therefore on the rise. While automated detection and analysis within cultural landscapes started early within archaeology (e.g. Lemmens *et al*., 1993; Redfern, 1997) the impact of e.g. automated monument detection is a recent phenomenon. This results in a demand for automated segmentation and classification strategies to cope with the large body of remotely sensed data and cultural heritage information. These trends are also visible in specialised sessions at the international *Computer Applications and Quantitative Methods in Archaeology* conferences.

To understand a field in the making, we turn to (semi-) automated procedures that help us analyse automated detection within cultural landscapes. We begin with a systematic literature review to get a first overview, and to retrieve a sample data set. In a second step, we use the applied statistics of network analysis to generate a new data set that contains patterns relevant for the dissemination of knowledge. Our goal is to see if and how publications form a coherent network or if research happens largely in isolation. This will help to show the formation of the field up to the present based on the impact of individual actors. Furthermore, we wish to see if automated analysis of automated procedures can point to potentially hidden developments that promise to advance the field in the future, which will be elaborated in the conclusion. In the conclusion we estimate trends and development regarding best practices within the field.

Method

Our analysis of patterns within automated procedures for cultural heritage and monument detection has two components: we begin with a Systematic Literature Review (SLR) to reveal overall trends. The overall trends are subsequently analysed using Network Analysis (NA) to gain a more detailed view of community structure and knowledge brokerage. The SLR uses Systematic Search Queries (SSQ) of bibliographic databases and citation indexes. The NA is based on a sample data set for referential connectivity. By looking at the historical development of the field through a quantitative lens, we hope to reduce personal bias and let the data of publications and citations do the talking instead. The results of our analysis can assist planning for similar projects by pointing to the hidden or missing connections of clusters of research. Throughout this paper the term 'monuments' will be used as the descriptor for visible cultural heritage in the landscape. This includes a large variety of architectural structures, but necessitates some physical entity possible to detect by remotely sensed data of satellite and aerial imagery, as well as LiDAR.

Quantitative approaches principally depend on the quality of their underlying data sets. Our dependence on qualitative data for our analysis is partly due to technical limitations in the citation databases. Without the ability to automatically generate larger randomised samples or to compare the topology of our graph with that of the complete corpus underlying our queries, we can only present an informed estimate of the real-world network. Just as these databases suffer from limitations in their collection process, e.g. collection based on English as lingua franca, they nevertheless provide a reasonably good estimate of different academic fields. Similarly, the core articles of our analysis present an estimate at the state of the field as it appears within these data sets. We welcome additions, corrections, and updates. All the data used for this study is freely available at the following hyperlink: http://dx.doi.org/10.11588/data/10083.

As time progresses, a more fully developed comparison between our model of the field, and similar models using more comprehensive data sets could refute or enhance our estimates.

Systematic Literature Review

Because the data for the SLR is collected from online publication indexes and SSQ, it produces a simplistic view for understanding the community and development of automated detection within archaeology. We used Web of Science (WoS)[1] and Scopus[2] as platforms for data extraction. Other potential databases for SSQ, are: Google Scholar, CINAHL, CAS Illumina Databases, EBSCOhost Databases, EMBASE, PubMed Central, Science Direct, and SciFinder Scholar. However, all the investigated online citation indexes provide a limited coverage of field's literary corpus. Thus, data fragmentation remains a problem for automatic extraction of data via SSQ because the corpus of articles lacks publications from lesser recognised journals and proceedings. Hence, qualitative selection of sample data sets enables a less impaired analysis in comparison to quantitative studies through online citation indexes. In its present state, online citation indexes are usually

[1] www.webofknowledge.com
[2] https://www.scopus.com/

biased towards different journals in relation to access obtained, or in-house publication. Consequently, comparisons between the different citation indexes are not defined as 1:1. Patterns can still be compared, because they are indications of overall trends. But it is necessary that they incorporate a large source material for data to be comparable. WoS and Scopus are two of the biggest citation indexes at present, and both incorporate a large corpus of publications focused on remote sensing and cultural heritage, such as *Antiquity*, *Journal of Archaeological Science*, *International Society for Photogrammetry and Remote Sensing*, *Remote Sensing*, and many more.

Figure 1 shows the results of the SSQ. The online journal and citation indexes indicate increasing relevance on the topic of remote sensing. By 2016 the data shows a reduced number of publications since we conducted queries in the spring of 2016. All queries combine two generic terms. More generic terms were experimentally queried, but few proved to show discernible patterns for dissemination of automated procedures in archaeological contexts. In addition to the selection bias favouring international peer-reviewed journals, a heterogeneous array of terms can designate automated procedures within archaeological practices.[3] All terms describe various advances towards automated and semi-automated means of segmenting and classifying remotely sensed data. The varied terms, however, make it difficult to locate specific tags that encompass all relevant data. Therefore, the SLR consists of generic terms to locate general tendencies and trends, such as: 'archaeology' (Ar), 'LiDAR' (Li), 'remote sensing' (RS), and 'automatic detection' (AD). These terms contain the largest potential data corpus for a SLR, but cannot reveal a complete picture. Especially in the combination with terms such as 'archaeology' the tendencies are much more fragmented. One such example is the combination of generalised search terms of 'automatic', or 'detection' combined with 'archaeology', resulting in two hits. Consequently, the more generalised search term 'remote sensing' has been used to see the presence in search queries together with 'automatic detection'.

The SLR reveals a prominent presence of remote sensing and LiDAR data within archaeology, but almost no relation to automated procedures. Within remote sensing the presence of LiDAR data grows exponentially. Equally, automated procedures grow parallel to remote sensing and LiDAR data within the online citation index of WoS, while Scopus indicates a more blurred pattern. However, none of the online citation indexes can indicate trends in the field of automated procedures for monument detection within archaeology. While other studies such as Tomljenovic *et al.* (2015) and Agapiou and Lysandrou (2015) effectively use SLR to enhance our understanding of remote sensing and automated procedures, we opted to use network analysis to complement our literature review. Network analysis reveals the community of automated procedures within archaeology, which is otherwise not registered by the SLR. Thus, where the SLR fails, the NA can elaborate and highlight more present, different, and miniscule communities and trends.

The timespan is defined by the possible extraction from the search queries of WoS and Scopus. Figure 1A illustrates the impact of 'LiDAR' data within 'archaeology'. Figure 1B illustrates impact of 'remote sensing' and 'archaeology', where usage history is extended back in time with increasing presence towards today. For 'remote sensing' and 'LiDAR', in Figure 1C, a clear trend can be seen for the presence of LiDAR data within remote sensing studies with high increasing presence and impact. Lastly, Figure 1D illustrates the tendencies for the search terms of 'automatic detection' within 'remote sensing' as well as 'archaeology' to show the difference in impact within these fields. It also illustrates problems for understanding automatic procedures within archaeology. Within remote sensing and automated detection, the field is exponentially growing, whereas within archaeology the picture is more blurred with few articles recognised by the online citation indexes. Some included articles are not even relevant, but as can be seen in the reference list and table of references,[4] many more articles of interest exist. But even though the SLR does not provide a complete picture, it still gives solid indications as to the larger trends in-between different fields.

Network Analysis

To gain a more fine-grained understanding of the regional and intellectual shape of the community revealed by the SLR, we turn to the tools of network analysis. By generating a citation network based on a new qualitative sample data set of 37 peer-reviewed core articles we can then trace the connections between individual publications and their authors, as well as the larger connected clusters that they form. Lastly, the overall shape of the graph allows for a tentative assessment of the connectedness of the field as a whole, and to visualize its evolution. The 37 core articles all apply automatic detection by either a data or model driven approach. We initially selected 40 articles maximising for different nationalities and

[3] The terms and keywords for the procedures are described by 'algorithmic procedures', general methods, as well as generic terms, such as: 'hough', 'canny', 'edge', 'line', 'shape', 'matching', 'extraction', 'detection', 'transform', 'object', 'template', 'attribute', 'texture', 'contrast', 'morphology', 'per-pixel', 'segmentation', 'classification', 'ontology', 'pattern', 'recognition', 'image analysis', 'automatic', 'semi-automatic', 'deep', 'machine learning', 'computation', and 'algorithm'.

[4] http://dx.doi.org/10.11588/data/10083

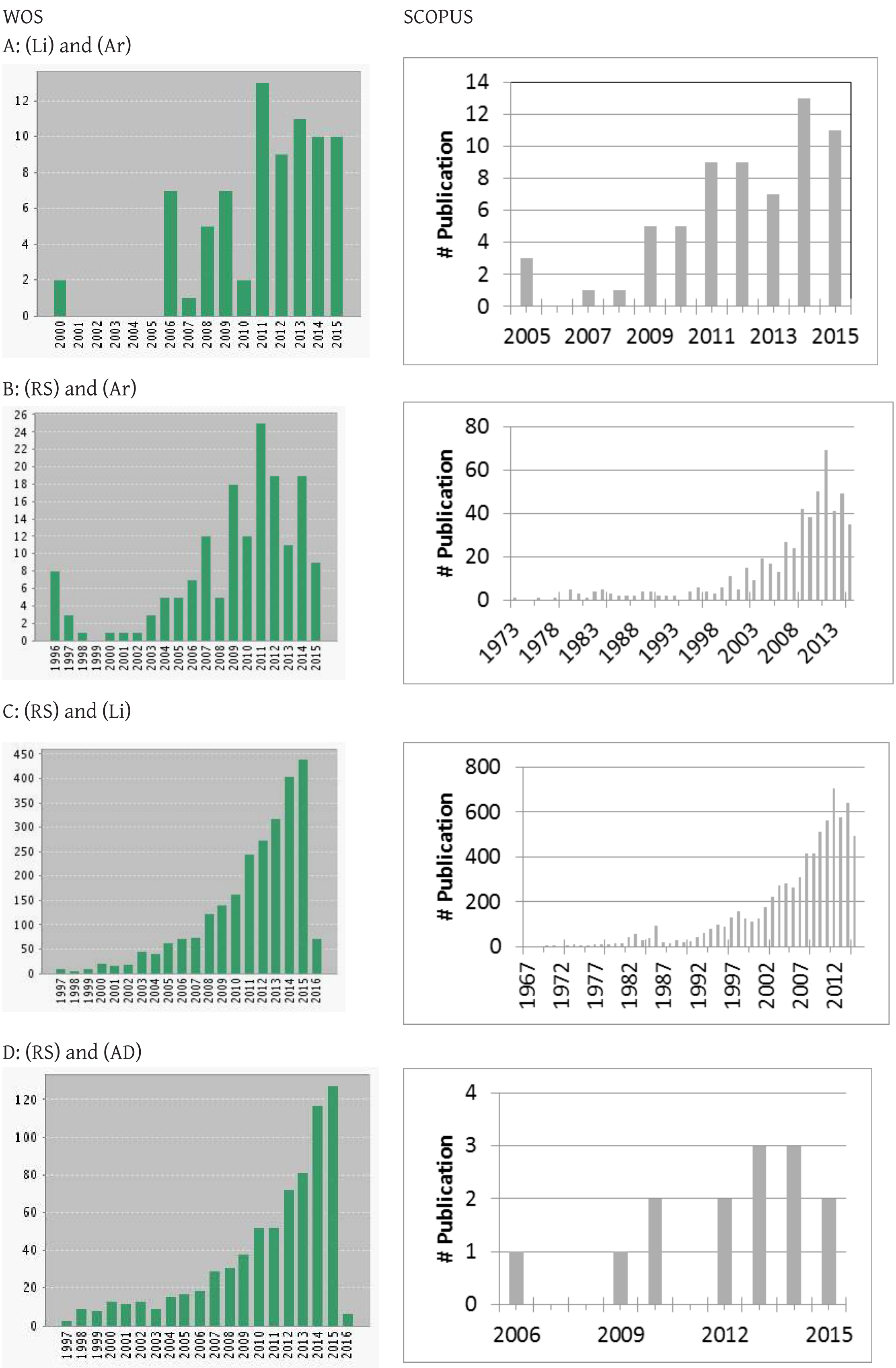

Figure 1. Scopus and Web of Science (WoS) citation index for publications combining:' Lidar' (Li), 'archaeology' (Ar), 'remote sensing' (RS), and 'automatic detection' (AD). The Y-axis indicates publication amount, whereas the X-axis indicates year of publication.

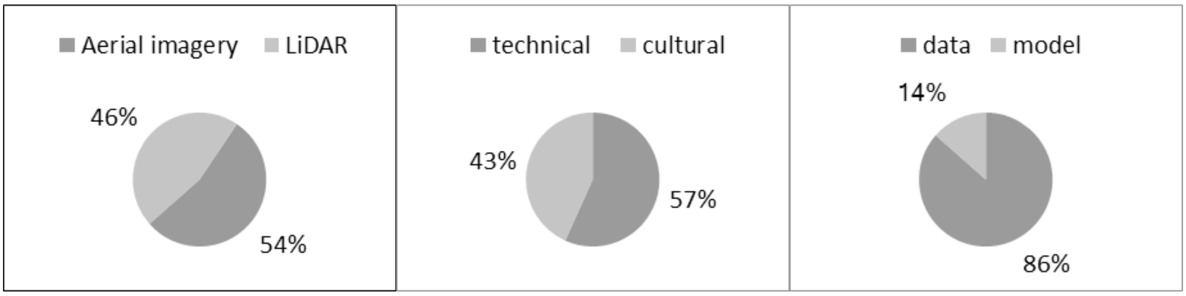

Figure 2. Focus within the qualitative new sample data set of 37 publications for the Network Analysis (NA).

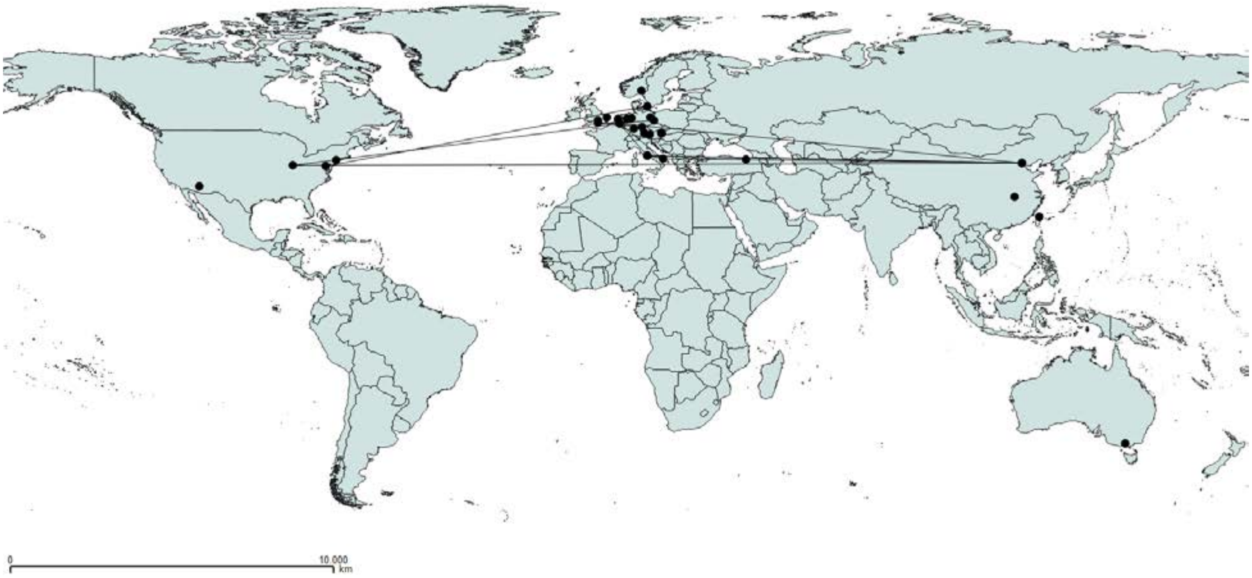

Figure 3. Institutional affiliations of the Network Analysis (NA) data set from 37 publications by first author.

for unique authors. We excluded three articles which only mentioned 'automatic detection´ but didn't apply it in their research. To minimise referential bias, we restricted the sample to one article per main author and excluded articles with high degrees of overlap between authors and co-authors between separate publications. The publications in the new NA sample do not represent all publications related to automated procedures for monument detection, but rather a diverse sample to probe the structure of connections between different aspects of the field. The resulting citation network consists of 1075 publication nodes and 1160 directed citation edges. It includes a variety of authors, and models the evolution of the field between 1999 and spring 2016. As a result, the connectivity of the graph puts further emphasis on intellectual brokerage between loosely connected components at the exclusion of self-references and repeated (re-) publications by identical groups.

The mean cooperation between authors is 1.105 per article. Within this selection (see Figure 2) 20 articles focus on aerial imagery from satellites and airplanes, 17 articles focus on LiDAR data. 21 articles concern technical questions, and 16 concern cultural heritage questions. A total of 32 articles focus on data driven and attribute analysis, whereas 5 articles specifically concern 'model driven' and 'template matching'.

Only a few articles include institutional affiliations of their authors at the time of publication, so information was manually supplied for the 37 core publications by first author. We can see in Figure 3 that the field has global reach, with a focus on Europe. This is likely a result of our institutional or linguistic bias, or of snowball sampling. A similar regional focus occurs with respect to places of publication from the bibliographical metadata. Yet, in today's publishing environment this has limited analytical potential, given the prevalence

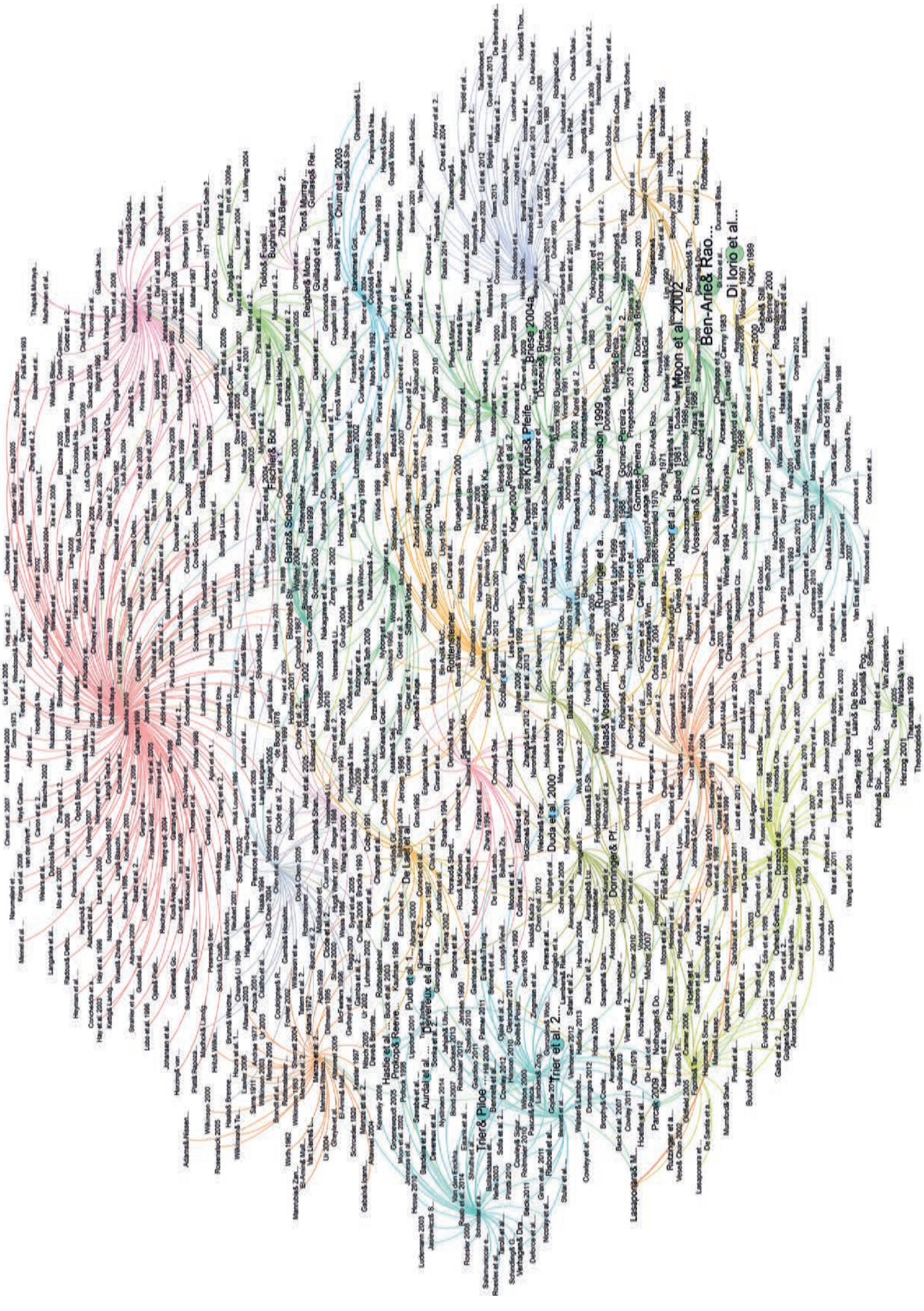

Figure 4. The full Citation Network.

of English as scientific lingua franca and academic publishing practices.

The citation network shown in Figure 4 uses Force-Atlas layout. This citation graph then forms the basis for applying community detection algorithms, further analysis of subgraphs, and event type information.[5]

[5] The network data and vector images for all graphs are available at http://dx.doi.org/10.11588/data/10083.

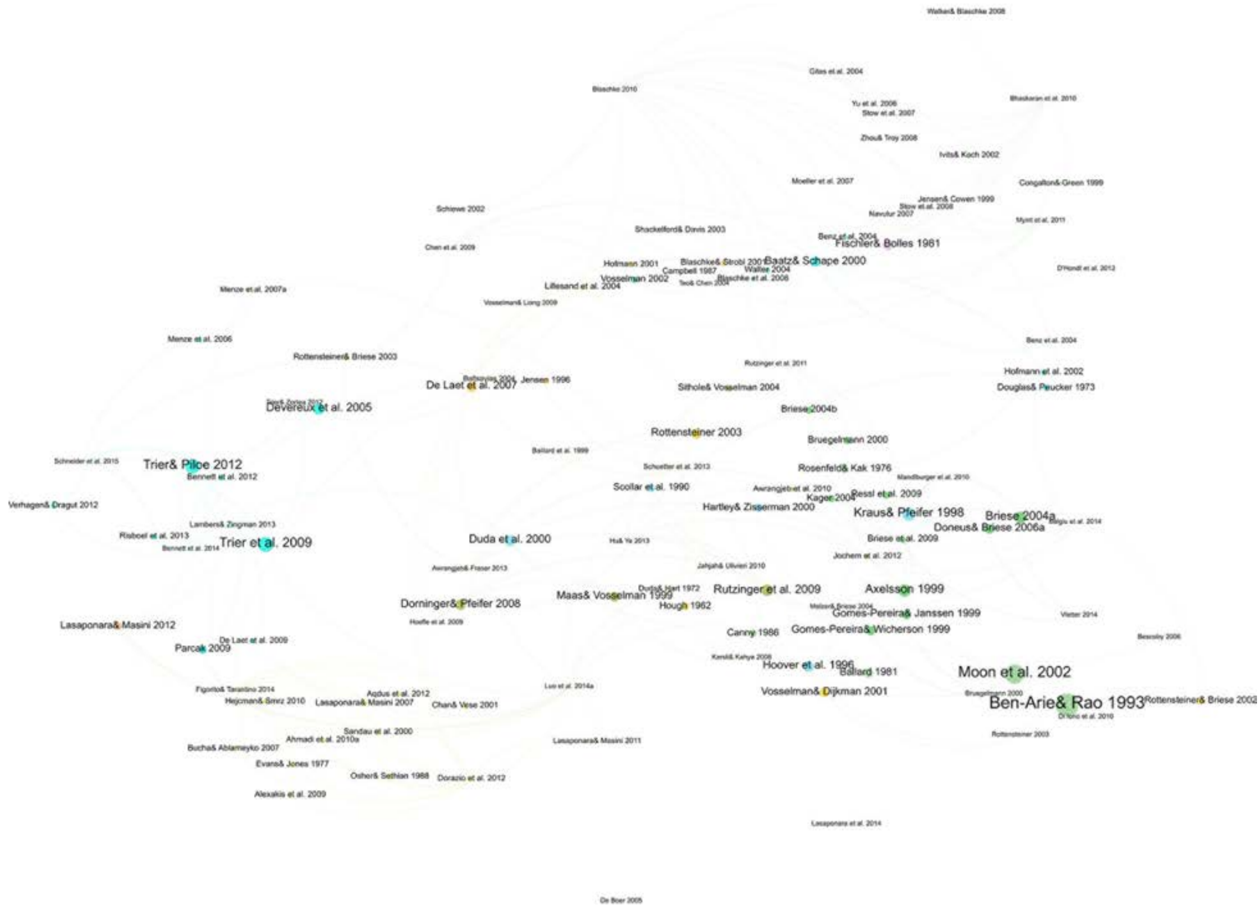

Figure 5. Subgraph Core Citation Network with degree > 1.

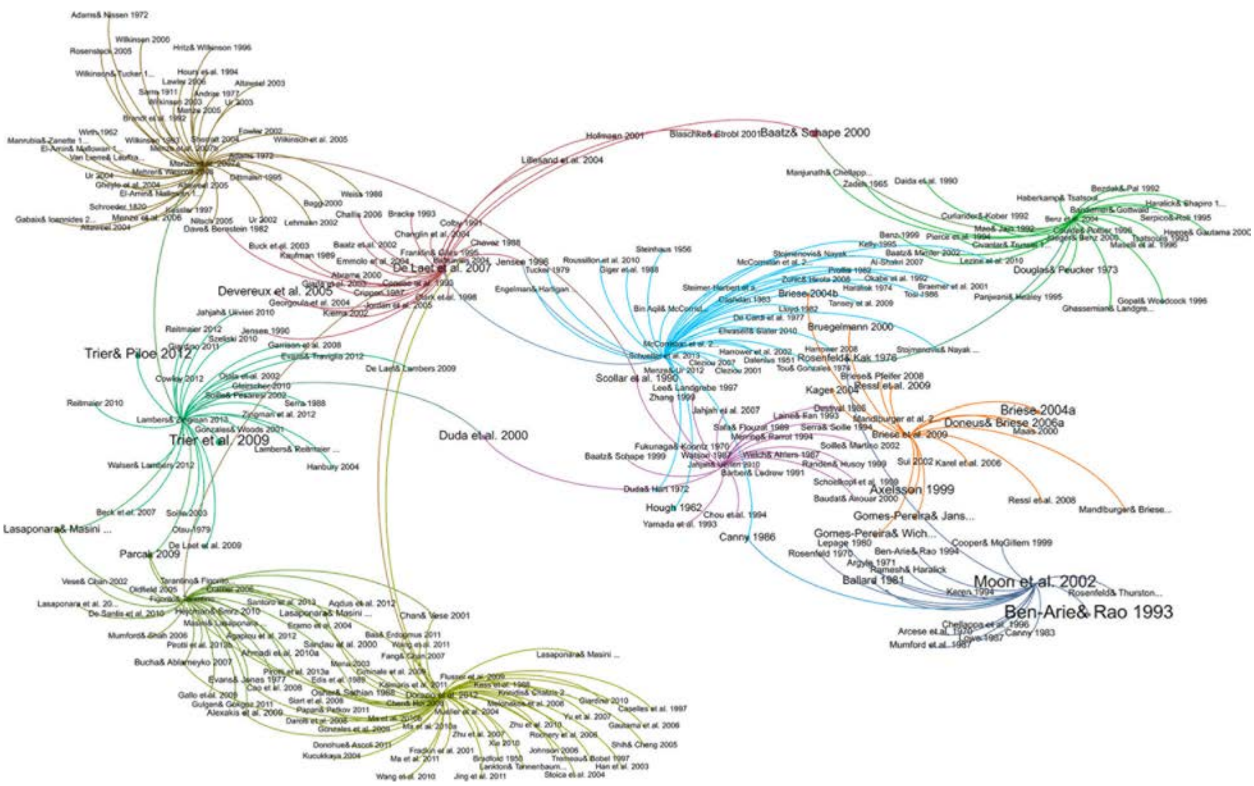

Figure 6. Subgraph In-citation.

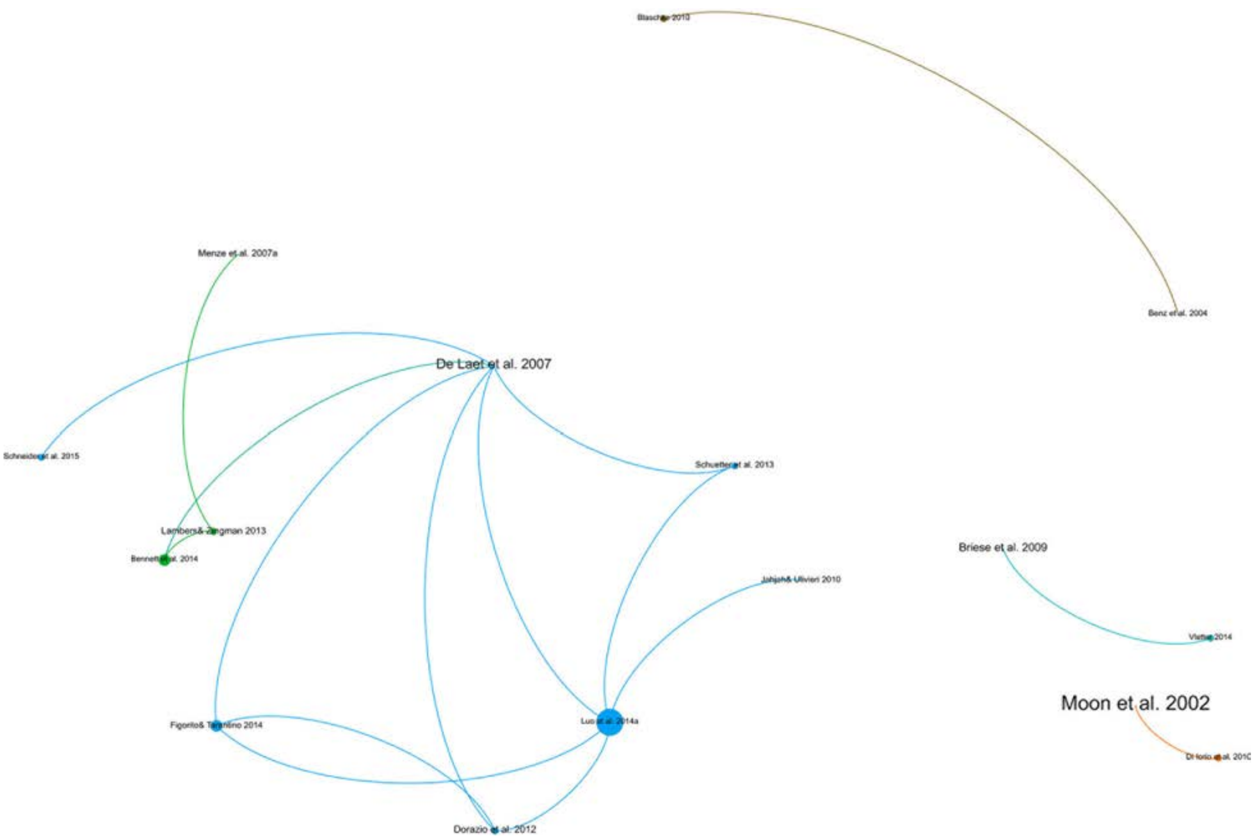

Figure 7. Subgraph Out-citation.

The relative position of nodes remains consistent from Figure 4 to Figure 7.

In Figure 4 pageRank (Page *et al*., 1999) determines both node and label size, by itself it is a good indicator of measuring academic impact. In the following figures, we contrast pageRank and centrality to assess the academic impact of individual publications (Yan and Ding, 2011). The prevalence of egocentric clusters such as the 190 mostly isotopic nodes related to [Blaschke 2010] (the big swirl at roughly 12 o'clock position) results in a sparse graph with a density of 0.001 and 4 main components. By filtering nodes with a degree > 1, Figure 5. Subgraph Core Citation Network with degree > 1 allows for a clearer view of those publications forming the well-connected core of the network (10.7% of nodes)

Again, the differences in node and label sizes are striking. These differences indicate competing ways in which publications are significant for the field. [Blaschke 2010] draws upon the most citations, but only a small part is in turn connected to the core group. [Ben-Arie and Rao 1993], on the other hand, occupies a central role for authors who in turn inspire other authors within the discipline. This becomes even more evident when comparing the subgraphs for in- and out-citations in Figure 6 and Figure 7. To derive these subgraphs, we ignore nodes which have zero in- or out-degree respectively, and subsequently filter isolated nodes from the remaining set.

In both cases [Moon *et al.* 2002] and [Ben-Arie and Rao 1993] play a significant role, albeit as part of small out-citation components. [De Laet *et al.* 2007] and [Luo *et al.* 2014] show the most consistent impact across all measures, along with others such as [D'Orazio *et al.* 2012] who rank in the top ten across different measures (see Figure 8).[6] This sequence of sub-graphs explains the discrepancy in impact that different means of measurement capture in the original citation network, and which we display here by modifying nodes and label size independent of each other

If we look at the evolution of the network over time in Figure 9. Time Series for Nodes and Edges we can see that a shared body of references is only slowly coming

[6] For detailed discussions of centrality algorithms we refer to the large body of general introductions to graph theory, http://barabasi.com/ provides a good overview. Roughly speaking Betweenness measures how often a node lies on the shortest path between two other nodes. PageRank adds a randomised element to this calculation to prevent loops, and centrality calculates the sum of a nodes connections.

RANK	PUBLICATION					
	Betweenness		pageRank (0.001...)		Degree	
1	De Laet et al. 2007[12]	154.5	Ben-Arie and Rao 1993[586]	...2129	Blaschke 2010[28]	191.0
2	D'Orazio et al. 2012[32]	87.5	Moon et al. 2002[21]	...1582	Belgiu et al. 2014[18]	69.0
3	Menze et al. 2007a[26]	82.0	Di Iorio et al. 2008[587]	...1582	Luo et al. 2014[35]	66.0
4	Lambers and Zingman 2013[13]	65.0	Trier et al. 2009[248]	...1008	Bhaskaran et al. 2010[10]	62.0
5	Schuetter et al. 2013[37]	32.5	Trier and Pilø 2012[249]	...0890	D'Orazio et al. 2012[32]	53.0
6	Benz et al. 2004[27]	24.0	Kraus and Pfeifer 1998[138]	...0691	Lasaponara et al. 2014[30]	44.0
7	Jahjah and Ulivieri 2010[34]	21.0	Axelsson 1999[114]	...0604	Menze et al. 2007a[26]	41.0
8	Figorito and Tarantino 2014[33]	20.5	Briese 2004a[115]	...0558	Myint et al. 2011[14]	39.0
9	Moon et al. 2002[21]	17.0	Rutzinger et al. 2009[143]	...0494	Schuetter et al. 2013[37]	37.0
10	Briese et al. 2009[2]	14.0	Devereux et al. 2005[244]	...0456	Chen et al. 2009[11]	37.0

Figure 8. Comparison of Top 10 Centrality Measures (multiple appearances in bold). Square brackets mark NA ID.

into being. While the articles in the data set were published between 1999 and 2015, their references go as far back as 1820 with the majority of publications (43%) falling between 2011 and 2015 as can be seen in the long-tail plot of the occurrence of nodes and edges for the whole graph. We cannot say conclusively that this indicates the conscious development of the field in light of its earlier history, but is very likely the case. When comparing the time at which new nodes enter the network with the time in which edges are formed, it becomes obvious that the formation of today's field first began around 2009 when a steep increase in the connectedness of the graph occurs, while the increase in nodes remains stable. Before 2009 most publications stand in relative isolation. Both the 2009 peak and a second peak in 2013 can be seen in the final panel of Figure 9 which tracks changes over time in the clustering coefficient.

Given that connectivity, overall size, rate of growth, and regional spread are continuously increasing, the question is less if the field is going to continue to grow, but how. Predicting the future growth of the network touches upon the question of preferential attachment (Barabási and Albert, 1999). Throughout the sequence of graphs from Figure 4 to Figure 7, hubs of various sizes are clearly visible. Given the kind of knowledge network that we are modelling such a non-random topology matches our expectations. In simple terms, those publications that have already attracted more attention are likely to continue to do so. When we compare the networks evolution with the predicted development of scale-free networks in Figure 10, we retrieve somewhat contradictory results. The graph for degree distribution shows strong linear tendencies, and the formation of hubs earlier than expected, which is reflected in a poor correlation between the predicted and the observed graph structure. The values for avg. clustering coefficient (and topological coefficients), however, show a better match between prediction and observation. Most back referenced publications before 1999 do not form hubs. After 1999 hubs form slightly faster than predicted by power law models. While the early history of the field shows a high degree of isolation from later developments, recent trends tend to strongly accumulate around hubs, which is likely to continue to influence the future formation of the field.

In summary, the network analysis shows a field with historic roots in the 19th century, experiencing intense spurs of growth and expansion. A high degree of ego-centric clusters impeded the formation of a truly connected whole characteristic for scientific communities. This, however, has been over-compensated in recent years, by a small number of publications that brought the fragmented parts of the network into contact. These brokers continue to unify the network to a higher degree than we would have expected. It remains to be seen in the following section what the causes of their performance might be. The data at hand is not suitable for a detailed inquiry into the regional and institutional affiliations for each node in the network at the point of publication. While these are likely to have shaped the formation of the network, we showed that the internal structure of the network is exerting its influence. By drawing connections between otherwise disparate research endeavours, the community we modelled is now in a better position to formulate informed responses to methodological challenges, or to avoid repeating past mistakes. How regional ties, methodological similarities, and intellectual brokers relate to each other forms part of our discussion in the following section.

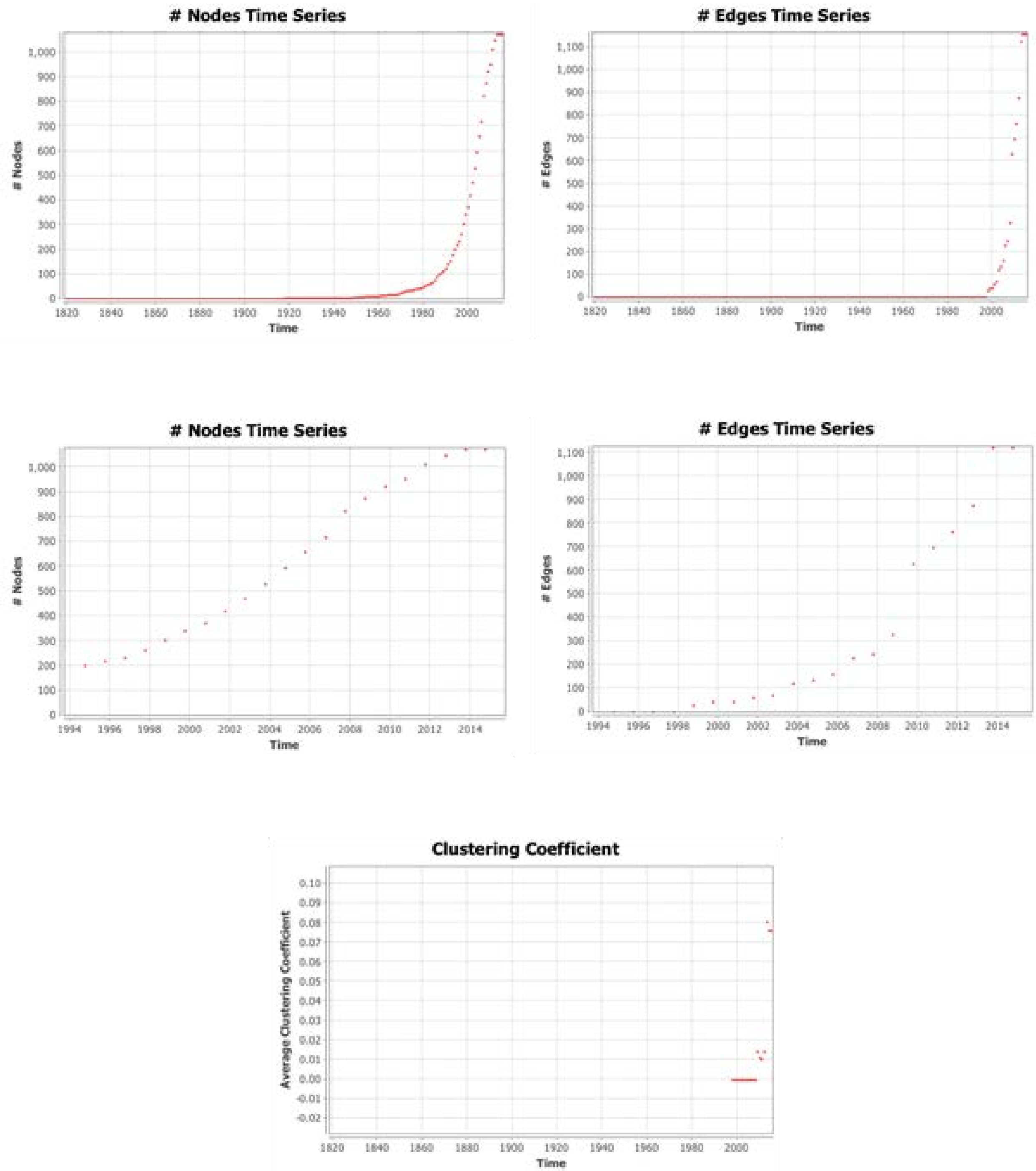

Figure 9. Time Series for Nodes and Edges.

Discussion and conclusions

Both NA and SLR point to the formation of a fast growing and increasingly connected discourse concerning automated procedures within archaeology. In the last part of this essay we wish to argue how the history of the field is likely to continue to shape its developments. Our analysis looks at the evolution of the field as it happens. This means that we fundamentally trust that praxis successfully spreading within the network are subject to selective pressures of standard academic review. What our methods cannot provide, are a theoretical foundation for or against new paradigms. By 2009 a well-connected community started to form. The observable imbalance between model and data driven approaches, means that those following the majority approach had an advantage through a larger body of established knowledge. For the evolution of the field, it remains to

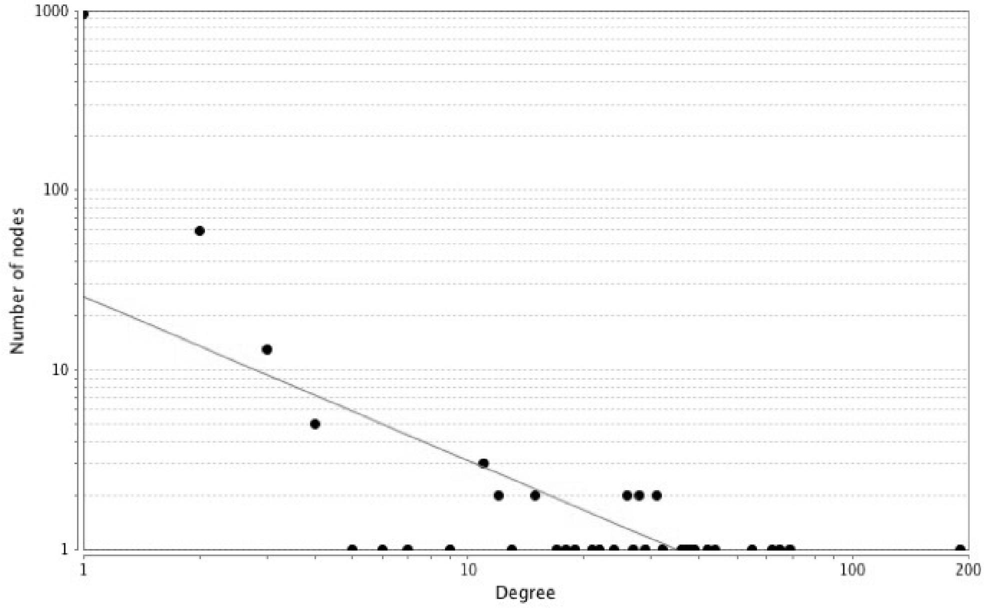

Fig 10A: Correlation: 0.840, R-squared: 0.512

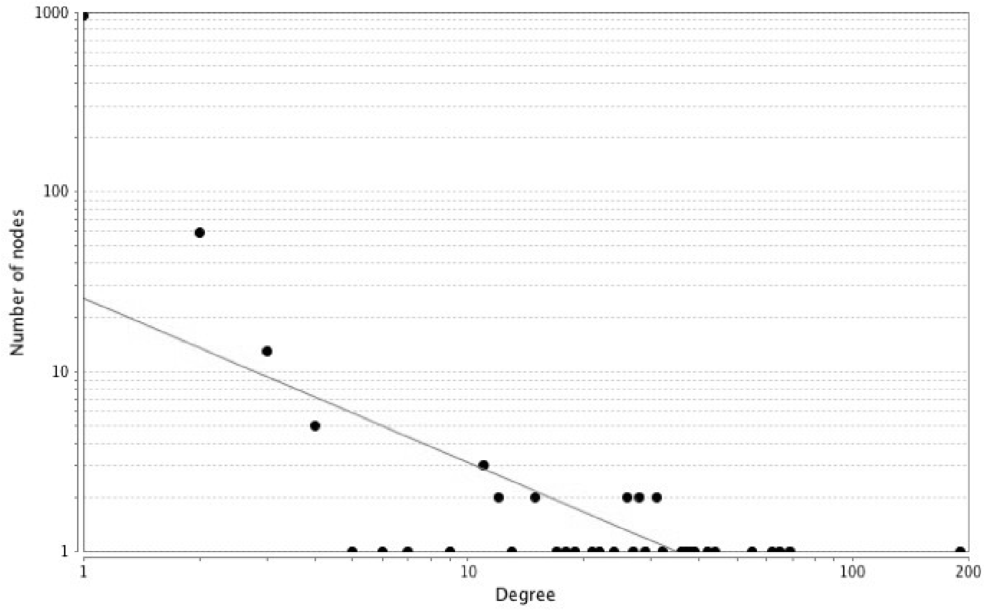

Fig. 10B: Correlation: 0.957, R-squared: 0.803

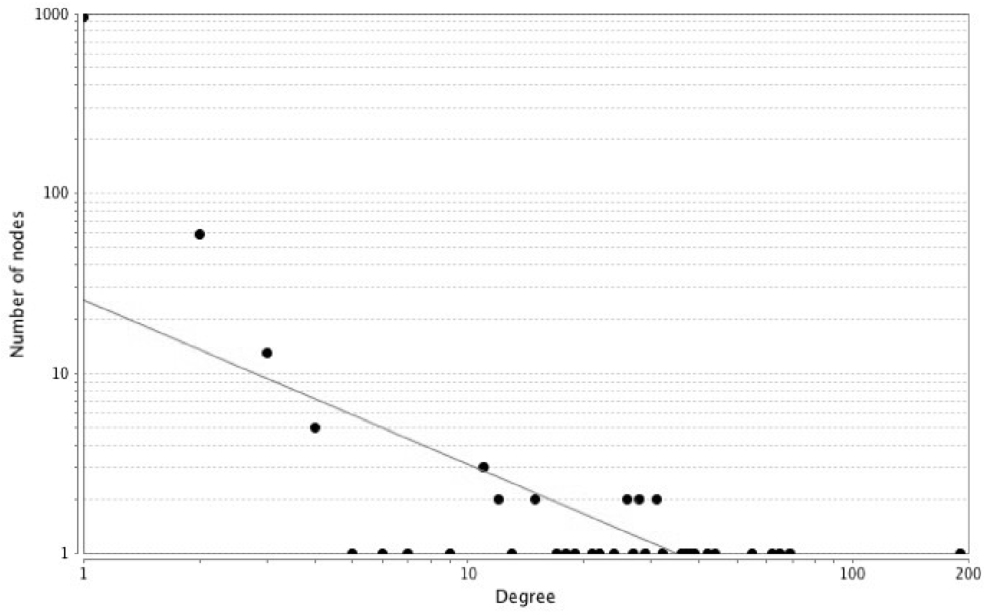

Fig. 10C: Correlation: 0.993, R-squared: 0.979

be seen if model driven approaches can counteract this structural inertia, or if they continue to stand in relative isolation within archaeology potentially forming links to entirely different knowledge domains.

The overall focus (86%, Figure 2) on data driven approaches for both automated procedures and automated monument detection has shaped the development of the citation network. The dominance of procedures by unique proxy values and per-pixel analysis signifies a long-standing search for standardised means of detecting hidden monuments in vegetation. However, with LiDAR data this has changed so that both data and model driven approaches are applied to previously untested areas.

Model driven approaches (14%, Figure 2) for automatic detection of monuments emerge in the mid 90'es, but with little immediate impact on the field. In this, the model driven community mirrors the data driven community around 1995 with many isotopes and small isolated components. More recently, it follows the general growth trend of a field consolidating itself. If we look at one example more closely we may explain how innovations generate impact without forming connections in the graph. Arjan De Boer's (2007) work on standardised means of automated monument detection, stands in relative isolation within the graph. Yet, despite its isolation, the methodological approach of De Boer (2007) regarding template matching and pattern recognition has found its way into the larger discourse of automatic detection and cultural heritage. This implies influence and collaboration from the field of computer science where these techniques are explored in depth under the heading of image analysis. The data lacks unambiguous references to research fields of collaborating authors, and therefore cannot accurately capture this implied influence. Our method can only capture innovation if it is expressed in the form of citations. Instances such as these are a reminder that knowledge advances along different trajectories during conference hallways, personal correspondences, and collaboration between fields. Future publications might still remedy this fact by forming new connections to earlier works.

From comparisons of best practice between model vs. data driven approaches we see that, it is not a transition from pixels to templates, but rather two techniques towards the same aim. (e.g. Brunelli and Poggio, 1993; Myint *et al.*, 2011; Pregesbauer, 2013; Sevara *et al.*, 2016; Tomljenovic *et al.*, 2015). Consequently, a combined approach will likely set the next stage for machine learning. Machine learning is a versatile means for working with multiple variables and data sources towards optimised detection algorithms (e.g. Krizhevsky *et al.*, 2012; Trier *et al.*, 2016). However, it is only briefly present in the citation network by reference from the core articles, while machine learning for automated procedures for archaeological practice were not registered by the systematic literature review from our structured search queries. As with De Boer's example, lack of connectivity is neither a sufficient criterion for novelty nor does it preclude impact. Instead intellectual brokers can often only be judged in retrospect. In our case, the pattern of isolation is similar to that of data and model driven approaches ca 1999 and 2010 respectively. Machine learning will likely evolve to form a discernible community with connections to both data and model driven communities. Looking at these patterns of isolation within our data, approaches combining all three elements are still insufficiently explored. In our view such combined approaches presents promising candidates for future research implementation.

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Bioarchaeology Module Loading...Please Hold. Recording Human Bioarchaeological Data from Portuguese Archaeological Field Reports

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Abstract

The Bioarchaeology Module as part of the Endovélico database maintained by the General Directorate for Cultural Heritage (DGPC) holds the record of archaeological and bioanthropological data. While primarily directed towards heritage management it has the potential to become a valuable tool to research by constituting a complementary record to the written archaeological field reports, making them more accessible for research.

The poster communication aimed to expose the particular case of entering data into a database pertaining to information concerning archaeological human remains in archived Anthropological and Bioarchaeological Reports. These not only cover a wide scope of chronological periods and territorial space but also, as the main archaeological archive of Portuguese archaeological grey literature, it has a diverse collection of documentation from early 20th century reports to the present day. We explore the issues brought on by terminology, data and the reports themselves and explore how these might be addressed.

Keywords: human remains, archaeological interventions, grey literature, databases

Introduction

The Directorate-General of Cultural Heritage (DGPC) is the Portuguese state's entity responsible for heritage management and, as such, houses the main archive of Portuguese archaeological documentation. This is in accordance with national heritage legislation, which holds the recording and inventory of information as the cornerstone for heritage protection and safeguard. All field reports from archaeological excavations are public and open to consultation locally upon request, since the vast majority of reports is still in paper format, although there is an effort underway to make the digitalised versions available for online consultation. This paper aims to be a reflection on our experience researching field reports, kept at DGPC's archives and with information pertaining to human osteological remains, and uploading the key field information to a database.

In Portugal, especially since the late 1990s as a result of a substantial increase of construction works and more comprehensive legislation,[1] in-field archaeological research is carried out mostly by private commercial sector archaeological companies[2] which must comply with national regulations and are supervised by the Directorate-General to whom they must request previous approval and submit a final report. The DGPC also manages and updates an information system database 'Endovélico', created in 1995 to aid and enable heritage management, which is in constant update and articulates with a GIS system. It is subject to several constraints, both financial and policy related, that hinder a full remodelling of the IT system and the number of exclusively dedicated staff both needed for an improvement of the database.

An ever evolving system, the latest addition to Endovélico was the development, in 2010, of a bioarchaeology module (Duarte and Neto, 2010), devised to record information pertaining to anthropological field work (grey literature) concerning archaeological human remains. The development of this module stems from an increase of on-site information pertaining to human remains recovered, in response to legislation that made compulsory the presence on-field of experts with human osteology background, responsible for the exhumation of remains and the production of

[1] That makes archaeological surveys mandatory, especially in historical areas.

[2] Although, municipalities are also often involved. There are also several research projects carried out by the Universities usually within the scope of annual or multi-year research projects.

an anthropology report to be annexed to the final archaeological report.

The potential of the bioarchaeology module

There are currently several types of database, ranging from simpler minimalistic databases that constitute a simple inventory to help researchers to locate skeletal collections, to more complex multipurpose databases that allow the refining of results through query based searches (White, 2007). Most databases are connected to specific projects or institutions and therefore focus on answering specific research questions, often assuming a set of common core criteria that are collected and recorded by members of the same team, while they also tend to be directed towards the collection of primary anthropological data sets or act as a repository of anthropological reports. The fact that the bioarchaeology module, as an integrant part of the Endovélico database, belongs to the DGPC means that it encompasses the whole national territory and a wide chronological scope, as opposed to the aforementioned project related databases. This also means that it stands a greater chance of survival, maintenance and constant update, thus surpassing the temporality of specific research projects. Consequentially, one of the key features of this database is its interconnectivity of information that ensures the preservation of contextual information pertaining to GIS, artefacts and all previous works carried out on the archaeological sites.[3]

Although Endovélico's aim is first and foremost directed towards ensuring heritage management efficiency, and as such it is an instrumental tool for DGPC's staff, its bioarchaeology module holds the potential to become a valuable asset for bioarchaeological research. It can become a solution to some problems commonly related with the study of human remains, such as the poorly publicised existence of collections available for study, which has dictated the dependency on word of mouth in order to identify the collections available, and the possibility to trace collections with desired characteristics for specific research questions (White, 2008). A case-by-case search of reports in paper format can be cumbersome without tools that allow for query based searches in order to identify which reports might hold relevant information. This is especially relevant since reburial is not a common practice in concern to Portuguese archaeological remains (Umbelino and Santos, 2011) exhumed from salvage and rescue archaeology, and as such constitute a source of untapped potential for further study, since apart from atypical cases of particular relevance, these remains are seldom studied further than the anthropological field reports.

Our input on data input

Despite the earlier creation of the bioarchaeology module, external constraints have delayed a regular upload of information into the module, but in 2014 an effort was undertaken to make a systematic upload of information onto the database and thus it was possible to demonstrate not only its great value and potential, but also to identify the need for a careful reflection regarding the reports themselves, the terminology employed and their data.

All reports kept at the DGPC are in paper format, and the majority also exist in digitised pdf format. The bioarchaeology module does not attempt to replace the reports, but to complement them, by becoming an auxiliary research tool to browse and query information more efficiently, in order to assist researchers to identify the reports of interest. In this way it will not only potentiate access to the information but will also ensure another form of digital preservation of part of the information, contributing to the prevention of digital obsolesce. The work consisted of the identification of reports that had information pertaining to human remains and the upload of anthropological information onto the database.

Field reports

As the main archive of Portuguese archaeology, to whom the reports are submitted and subsequently housed for storing, preservation and consultation, it covers a wide chronological scope that reflects the history of Portuguese archaeology in itself, comprising reports dating from 1939 to the present day (Neto and Seabra, 2015). This means that these reports, despite maintaining a constant technical and informative character with the purpose of informing the State in regards to its Heritage, they cover the passing of several schools of thought and approaches regarding archaeological[4] practice up until Post-Processual Archaeology (de Alarcão, 1996). This is illustrated not only in the methodological approaches but also in what concerns the importance given to human remains excavated from archaeological sites. Through these documents it is also possible to observe the results from changes in legislation, that has become increasingly more complex, as well as the appearance of multi-disciplinary approaches with the involvement of field, conservation and other experts. In the particular case of human remains, it is possible to see a transition from near neglect — absence of

[3] This is already possible to some extent in regards to archaeological information, which is available through the Directorate General's online Archaeologist portal http://arqueologia.patrimoniocultural.pt/

[4] And to a certain extent anthropological practice, particularly its increasing involvement in the field.

information regarding the subsequent destination, for example — to their exhumation for subsequent study usually by researchers with medical background and anthropologists, however in the earlier times their results and conclusions were seldom included. The presence in-field of an anthropologist during the excavation of archaeological sites with human remains started to emerge during the 1980s but only in 1999 did it become required by law[5] and ceased to be dependent on the excavation director's choice (Umbelino and Santos, 2011). Subsequent legislation in recent years[6] has contributed to further define and strengthen the position and contribution of anthropologists in the field, which not only reflects the specific way in which archaeological human remains are perceived, but also the influence of the notions of Anthropologie de Terrain (Duday *et al*., 1990; Duday, 2009) and the recognition of the importance of on-field observation.

So, with respect to the database, what criteria should be used to select the anthropological reports to be included? Should the sparse information from older reports be included, and if so, in what way should it be made available? This could aid the re-use of older information sources that can still have something to offer to current research (Tõrv and Peyroteo-Stjerna, 2014).

Terminology

As we have mentioned, most rescue and salvage archaeology work is undertaken by commercial private sector archaeological companies and freelancers, duly accredited and recognised during the request submission by the DGPC. As a consequence, the work and subsequent reports are done by a very diverse group of professionals, who graduated from different institutions and have different research interests. This means that, although there is limited standardisation in terms of *ad minima* criteria required by the DGPC, the way that this information is collected can be quite different, which may hinder inter-observer analysis (da Cruz, 2011). It is also to be noted, that the same author tends to use terminology indiscreetly and synonymously using many terms at certain times, and at others using the same terminology to mean different concepts, as there are not current standards for terminology. This is not a situation exclusive to Portugal, and many authors have stressed the importance of a common core of standardised terms (Knüsel. 2014; Knüsel and Robb, 2016). This is of particular significance since a certain level of standardisation is always required when dealing with digital platforms and databases. We are aware of the difficulty of this task, especially because the database has a great chronological and spatial scope and the same 'term' can be more or less appropriate depending on the specific period and context. Care should also be taken when adapting foreign terminology that was devised taking into account different realities which may or may not apply to the Portuguese context. It is of utmost importance for any progress to be made regarding any database to find a good balance between standardisation and the specificities and uniqueness of each record, so as to avoid a 'forced' standardisation of the archaeological record.

Data

Finally, when considering the information to be inputted into the module, it is crucial to decide what type of data to include and in what way it should be included, e.g. closed entry check box, drop-down lists or open text. While there isn't much doubt on the value of some information, like the sample size and state of preservation, and place of deposit, other types of information, regarding funerary practice, age-at-death, sex and even paleopathology and taphonomy, could be very useful assets to filter or pinpoint collections of interest. How much detail should be provided? In a way this becomes a matter of determining what data are 'relevant' and what becomes 'noise' (White, 2008; Elton and Cardini, 2008), a selection that not only varies greatly according to particular research interests but also is impossible to determine what data will be relevant in the future. Cases can be made for both minimalistic approaches and more comprehensive data collection, which can be of more value in the long run (White, 2007; Elton and Cardini, 2008). On one hand a simplistic approach is less likely to lead or prejudice the researcher into assuming conclusions — for example a sample with a pathological condition that was not detected on field would risk not being studied because a filter search would not identify it as a relevant result. A minimalist database would certainly have the advantage of being more cost effective and easier to update and maintain. No doubt, however, that more complete and comprehensive data sets would be much more useful for filtering results efficiently, especially when sieving through big quantities of information. These would provide not only a management tool, but also a way to browse reports to be consulted as opposed to a means to substitute the reports themselves.

The type of remains themselves have also been under consideration, since there has been a tendency to underestimate the importance of disarticulated osteological remains; they have come to be seen as too time consuming for the amount of relevant information that they can return. This is especially the case in the context of commercial archaeology bound to strict

[5] Regulation of Archaeological Work decree-law n. º 270/99, 15th of July.

[6] Basic Law of Cultural Heritage n. º107/2001 of 8th September; decree-law n.º 164/2014, of 4th November and Circular Nº 1/2014 biological anthropology in archaeological contexts.

deadlines and budget (Brickley, 2004), which must be negotiated with the contractor or developer, who is responsible for the costs by law. However, one could argue that the increasing methodological advances will have a tendency to improve cost-benefit over–time through, for example, easier access and cheaper laboratory examinations.

In summation

The bioarchaeology module is different from other databases, in the sense that it aims to integrate information on a broader scope, focusing on remains that have only been studied in the field during exhumation by different teams and specialists nationwide, covering the entirety of the national territory and a wide chronological scope. The fact that it is managed by the DGPC further ensures the potential for continuous update of information and maintenance. The database has the capacity to potentiate the scientific value of the exhumed remains, by enabling their disclosure and availability. Furthermore, we are certain that the difficulties identified can be overcome, although this is a work in progress with a long way to go. We consider it to be necessary for the engagement of the professional and scientific community, as well as to raise awareness to the importance of issues pertaining archive maintenance and survival of information.

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Methodological Tips for Mappings to CIDOC CRM

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Abstract

This paper presents some modelling principles and methodological good practices that have been empirically derived from the systematic mapping of diverse cultural data sets to CIDOC CRM and its extensions, using the X3ML mapping framework in support of several Cultural Heritage projects. Learning to apply an ontology in a mapping is similar to learning a language. There are certain basic formulations and problems that most learners will run into in executing their first mappings. This paper therefore discusses how to understand and carry out the process of mapping in general, developing an explanation of what it is to map source to target schemas, and how to practically achieve this in the best and most efficient manner. It then explores thematically particular issues that the results of our research have shown as common problems faced by beginners to semantic mapping, providing solutions and rules of thumbs to apply to these common problems.

Keywords: CIDOC CRM, mapping technology, archaeological databases, cultural heritage information systems

Introduction

This paper will present methodological principles and rules for application by domain experts wishing to conduct mappings of cultural heritage information into the CIDOC CRM.

The research that this work is based on derives from recent experience in the implementation of CIDOC CRM in large scale networks using semantic technologies. CIDOC Conceptual Reference Model (CIDOC CRM, 2017a) is currently being implemented as the core model for use in several large-scale, international Cultural Heritage projects including ARIADNE,[1] ITN-DCH,[2] PARTHENOS,[3] ResearchSpace,[4] American Art Collaborative[5] and WissKI[6]. Clearly, one of the foundational activities of these projects has been the effort to convert the data stored in existing schemata to an expression in CIDOC CRM, and its extensions, with the goal of enabling information exchange and integration within their networks. To support the scalability of these activities, which entail careful analytic work by someone familiar both with the domain and with the ontology, a series of training events were initiated aimed at domain experts to introduce them to data mapping techniques. These workshops provided the perfect test conditions for analysing and understanding the primary practical and conceptual challenges experts face when first learning semantic mapping.

A significant number of mappings to CIDOC CRM have been developed during the last 20 years (CIDOC CRM, 2017c), using a formalism based on the declaration of equivalences and the interpretation of each source schema as a set of nodes and links. Such mappings were used to validate the CRM, to preserve data in a neutral form and served as guides for good-practice data structures.

The results of this research will be presented in three parts. In section 2, we present CIDOC CRM, its suitability for integrating and aggregating cultural heritage data, a definition of the mapping process itself and the tools we use. In section 3, we will present a practical methodological approach to the task of mapping: what one should consider in order to properly frame and execute a mapping. In section 4, some of the most common issues encountered when creating first mappings are presented and solution proposed. Throughout the paper, CRM classes are written in bold and properties in italic.

The mapping process

The CIDOC Conceptual Reference Model is a formal ontology that has been developed for integrating and aggregating information expressed in cultural heritage data sets. It is officially defined as providing, '*the "semantic glue" needed to mediate between different sources of cultural heritage information, such as that published by museums, libraries and archives.*'

The CRM was selected as the mapping target for integration in several projects because of its stable

[1] http://www.ariadne-infrastructure.eu/
[2] http://www.itn-dch.eu/
[3] http://www.parthenos-project.eu/
[4] http://www.researchspace.org/
[5] http://americanartcollaborative.org/
[6] http://wiss-ki.eu/

development process and the living community of curators that have maintained and developed the ontology over the past ca 20 years.

CRM is especially suitable to use as an integration language for large-scale Cultural Heritage (CH) projects because it provides a stable main ontology that supports an open-ended strategy of either local or systematic extension. The main CRM standard generalises only stable concepts and relations for information sharing, while local extensions are encouraged where necessary to capture local concepts/relations and practices. These extensions are developed modularly and hooked back into the core model creating an open 'family of models' which provides powerful query possibilities. All general facts can be reached by querying general concepts while detailed, more specific facts can be reached by querying the specialised extensions. The properties of the extensions are covered by super properties of the core model, in contrast to the so-called 'application profiles' which consist of a predefined set of metadata elements defined for a particular application. In the CRM approach interoperability can be achieved without restricting the data to a 'core vocabulary'.

Mapping a source schema to a target schema entails the provision of a sufficient specification for the transformation of each instance of the source into the target, such that the meaning of the former is essentially preserved in the latter. We consider that the source, of whatever form, presents a series of propositions about the world that are to be re-expressed in the target. Therefore, we read the source as if it were a semantic model and aim to interpret it as a series of nodes and links, where each element of the source is mapped to an equivalent CRM element with the same meaning. In practical terms, the most commonly encountered source schema is a relational model. In order to execute an interpretation of a relational schema into a semantic model, we interpret tables and columns as entities; individual records as entity instances; fieldnames as pointing to relationships and entities; field contents as entity instances. Each field in the source is interpreted as expressing a proposition in the form of an entity-relationship-entity (e-r-e) schema, and the whole source schema is decomposed into a series of such statements expressed in terms of CRM.

Figure 1 presents, as an example of data, one record from the Science Museum of London database.

Mapping is a time consuming and challenging process both intellectually and practically. Moreover, the activity is usually executed in a one-off fashion where intellectual effort behind the mapping is not preserved. In semantics, however, the value of mapping work cannot be underestimated. The work of each mapping may help solve a problem for any other mapping project thereafter. In the context of our research into training in mapping skills, we were precisely interested in capturing and displaying some of the main problems encountered by beginner users of CRM for mapping. For this reason, we adopted the X3ML Toolkit (FORTH ICS, 2017) for mapping. This toolkit uses X3ML (Minadakis *et al*., 2016; Marketakis *et al*., 2016), an XML based language which describes schema mappings in such a way that they can be collaboratively created and discussed by experts. It is designed to be independent from a specific encoding paradigm and is going to be implemented for all transitions between relational, XML[7] and RDF[8] schemata. We have extensively used 3M for mappings from XML schemata to the RDF encoding of CIDOC CRM. 3M gives learners of the mapping process a practical tool for undertaking this task and gives trainers a way to monitor the mappings created, to identify common issues and problems.

General mapping principles and approach

The first step during the conversion of an existing, source schema to an expression in a CRM compatible form (e.g. RDF), is to identify the general domain of discourse in which the source database is elaborated, and to determine the appropriateness of the target ontology to support statements in that overall domain. CRM is conceived for the general description of cultural heritage information. It would therefore be appropriate, in a general sense, for any source schema within the domain of CH. That being said, the wider family of models (CIDOC CRM, 2017b), which at present, provides specialisations in a number of fields — bibliographic information (FRBRoo, PRESSoo), digitisation processes (CRMdig), geospatial analysis (CRMgeo), scientific observation (CRMsci), archaeological excavation (CRMarchaeo), archaeological buildings (CRMba) and argumentation (CRMinf) — may provide a set of classes and properties more appropriate for the particular data to be modelled. Reading the intended scope of potential ontologies and getting an overview of the proposed classes and properties, is the starting point for choosing the most relevant ontology to translate one's data into. Specifying a set of ontologies as a target is possible so long as they are compatible or relations are built between them. In the case of CRM, the harmonisation process between the main ontology and the extensions ensures this compatibility *a priori*.

Once one's target ontology schema has been chosen, the analysis of the source schema in terms of the former can begin. Each table in a relational database can be considered as a documentation tool for recording information with regards to some class of entities.

[7] Extensible Markup Language (XML) https://www.w3.org/XML/
[8] Resource Description Framework (RDF) https://www.w3.org/RDF/

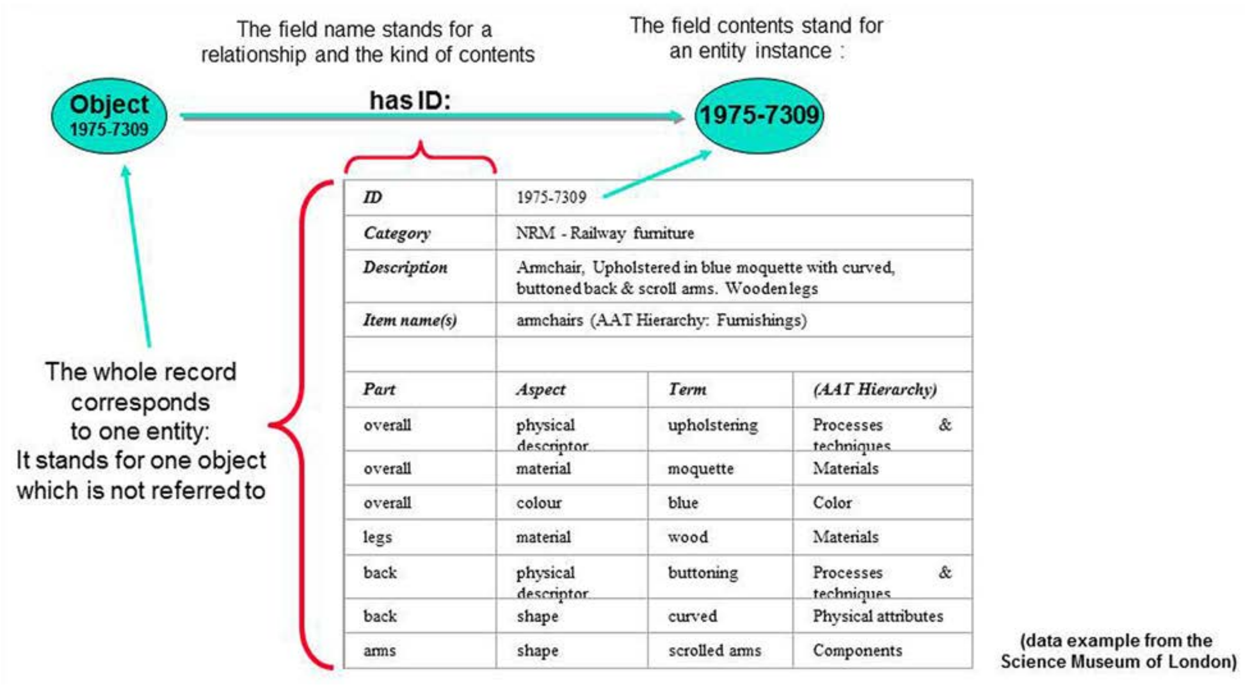

Figure 1. Interpreting a relational schema into a semantic model.

Thus a review of each of the tables should be done to attempt to understand what each of them documents. Sometimes this will be straightforward, with the table having a reasonable name describing the kind of records it holds and the record instances, in turn, conforming to what could be expected from the table name; sometimes, not. Going through the fields within the table, reading each as the description of a relation between this object and other objects, gives an overall feel for the kinds of statements that the source schema means to express. Next the target ontology should be reviewed, to understand the range of classes and properties offered. While no one will read an ontology in a linear fashion, users should acquaint themselves with the top level of CRM or any ontology, reading the scope notes for the top level classes and properties and understanding what they are meant to express. When deploying extensions, the extended expressive power of the additional classes and properties and how they relate to the main ontology should be assessed. Users should naturally also focus their intensive reading on the classes and properties that seem most likely to support the kinds of entities that their source schema describes.

For each table in the source schema, an appropriate CRM class must be chosen to represent it. To do this, the mapper will need to identify the primary domain of the source schema. The primary domain typically represents the focus of interest in this table. The class chosen to represent it in CRM will become the primary target domain for the mapping of this table. For instance, if the source data set is a numismatic database, a likely table in the data set will be a coins table. The primary domain is the coin entity. The objective of the mapper is to find the appropriate class in CRM that will be true both to capture the nature of coin, but more importantly the statements that the source database wants to make about a coin. Again, if the source data set is a museum's collection management system, the primary domain of one of the tables is likely the museum object. This may entail significantly different statements and interests than a coins table, therefore another class may need to be found to represent this object in CRM. How is this accomplished?

Users of the CRM can engage in a basic decision procedure to find the most adequate class to represent their primary domain. This decision procedure is initiated from the start of the class hierarchy and works downward. As users become more familiar with the ontology, they will easily jump further down the ontology branches towards the most appropriate area of the ontology. The procedure here is to follow the intersections of the class hierarchy and eliminate possible paths. At the top of the hierarchy, there are high level distinctions that will allow a quick decision: whether the primary domain is best expressed as an object, an event, an actor and so on. As one works downward in the class hierarchy, the choices will become more difficult as the distinctions become more refined. At a lower level one may have to choose between identifying something as an instance of a symbolic object or of an information object. To make a decision on the appropriate class at this level of distinction, it is important both to know how to read the ontology and to understand what the source schema wants to say.

Each CRM class is described by:

- **Number and label**: constitute the class identifier. The label does not necessarily correspond to the exact meaning of a class and thus it should not be used as the basic criterion for the appropriateness of a class.
- **Subclasses/Superclasses:** the position of a class in the IsA hierarchy
- **Scope note:** provides the exact meaning, the intension of a class. It is the most important section to consult for appropriate class selection.
- **Examples:** help to verify the correct interpretation of the scope note
- **Properties:** provide the relationships with other classes and can further assist in the selection of an appropriate class

The careful examination and understanding of the function of the above information is crucial to identifying appropriate classes for mapping to. Class labels should not be confused as providing the meaning of the class. This is a common first mistake. A class can only be understood by reading its scope note, which provides a human readable definition of the use of the class. Can the class intension reasonably be interpreted as describing the primary domain? If so, then the next step is to check the properties declared for the class. The class is only the starting and end point for producing statements about some subject. It is the properties associated to a class that enable the rich semantic expression where all the relevant information with regards to the instance can be found. Therefore, the properties defined for the class under consideration should be compared to the fields in the source schema. The mapper must ask themselves if this set of properties will allow them to properly express the fields in the source database table. Are other properties needed? If yes, then check a more specific class.

The mapper should always have in mind the power of the IsA hierarchies. The IsA class hierarchy means that each class that falls under another class (a subclass) inherits the properties of the class above. Going down the IsA hierarchy, classes become more specific. This means that one can search for a very specific class with very particular properties and yet still invoke very general properties. This structure further guarantees that if there is no specific class that fully captures the semantic property of interest to the mapper, there is at least some higher level generalisation that can be used as a compromise class to capture the general meaning of the source.

When no appropriate class is found for expressing the source schema's primary domain, it is necessary to consider the declaration of a new class either for local needs or as part of a potential general extension of the standard. The need for a new class arises if the mapping requires properties that are not available in CRM or its extensions in order to accurately translate the source. The introduction of a new class should comply with the 'Minimality' modelling principle of CRM (CIDOC CRM, 2017a):

> 'A class is not declared unless it is required as the domain or range of a property not appropriate to its superclass, or it is a key concept in the practical scope.'

For example, if the primary domain is the coin, there are two possible approaches to map it with CRM.

- Introduce a specialisation of **E22 Man-Made Object**:
  Exx Coin subclassof **E22 Man-Made Object**

- Use a typed **E22 Man-Made Object**:
  E22 Man-Made Object. *P2 has type*: **E55 Type** = 'Coin'

To choose between these two options requires an analysis of the source database table's fields and the properties available for **E22 Man-Made Object** and each of its superclasses. **E22 Man-Made Object** is proposed because the mapper finds the closest parallel to the coin construct of the source domain is the man made object construct of CRM. Semantically, the coin is adequately represented by the second option above just in case there is nothing else in the source that wants to make a statement about the coin that is not covered by the generic properties of an instance of this class. If, for example, the source has a field like 'Minting Year', we may begin to search to see if this can be described by the available properties. In this case, it can, through a production relation to an instance of **E12 Production**. However, an additional field in the source might be 'obverse' and a description thereon. Here again, we must analyse what is intended in the source schema and find if an appropriate property is available.

The process of mapping is not automatic but an iterative intellectual process that requires moving back and forth between reading and understanding the source and then determining the classes and properties that will allow the statements in the latter to be expressed in the former. Above we have attempted to describe the general procedure that the domain specialist undertaking a mapping must follow. Below, we will outline some of the generic problems that experts engaged in first time mappings to CRM encounter and

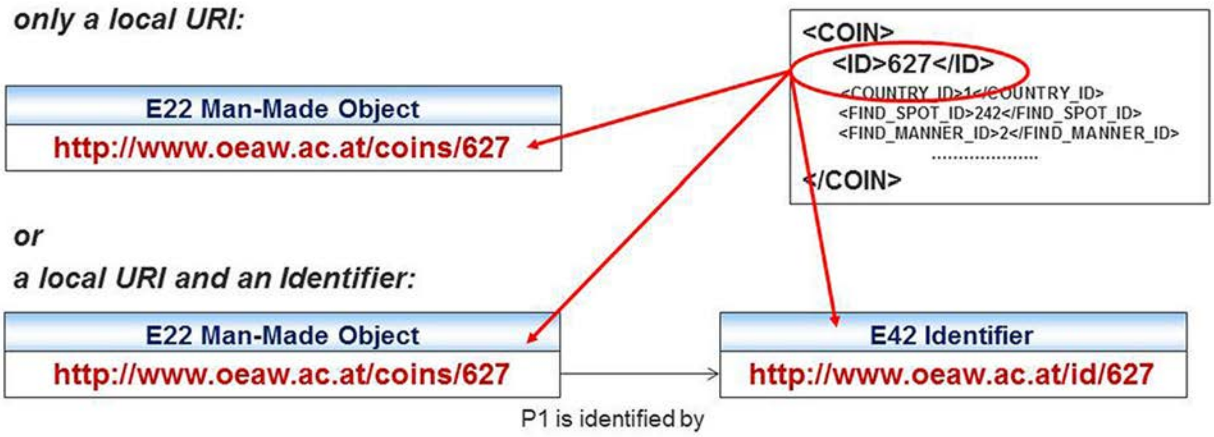

Figure 2. Custom local identifiers.

give an outline of what factors to consider in order to resolve these problems.

Practical mapping tips

While there is no rule book or one size fits all recipe for creating mappings which, by their nature, require precisely an expert's understanding of the semantic content of the data structure to be mapped, there are, nevertheless, common problems faced by all users who begin to carry out CRM mappings. Here we have addressed these issues according to the broad categories of common database fields, people, places and objects, broken down into specific problems.

Common database fields: local identifiers

Local identifiers in relational databases or other content management systems need be mapped explicitly only if they are visible in the user interface and used in other documents as well. The point of mapping is to bring all the semantically relevant data from the source schema into the target. Internal IDs of relational databases usually play only a functional role within the management of the database from the backend perspective, and are not used in scientific discourse to refer to or find the documented entities. Local database identifiers can, however, sometimes be re-used in a semantic context again for a new functional role, using them for generating URIs for the record instance (see Figure 2). This approach is suitable for identifiers of objects that belong to the owner of the database or that were generated by him/her and which would not otherwise have been given a more commonly known identifier.

Figure 3. Global authorities for local identifiers.

In all other cases, however, it is suggested to use a global authority. For example, El Greco (Dominico Theotokopoulos) is modelled as an **E39 Actor** and the identifier for this record can be taken from the VIAF or the GETTY ULAN's identifiers (see Figure 3).

In general, good identifiers should be widely known for the item they identify and they should be related to those who can confirm the relation between the identifier and the identified.

Common database fields: Appellations

The RDF class rdfs:label and CRM class **E41 Appellation** are alternative implementations for the same concept in RDF, a human-readable name for the subject. So, for simplicity, when mapping contemporary names into RDF, we suggest the use of rdfs:label tagged with

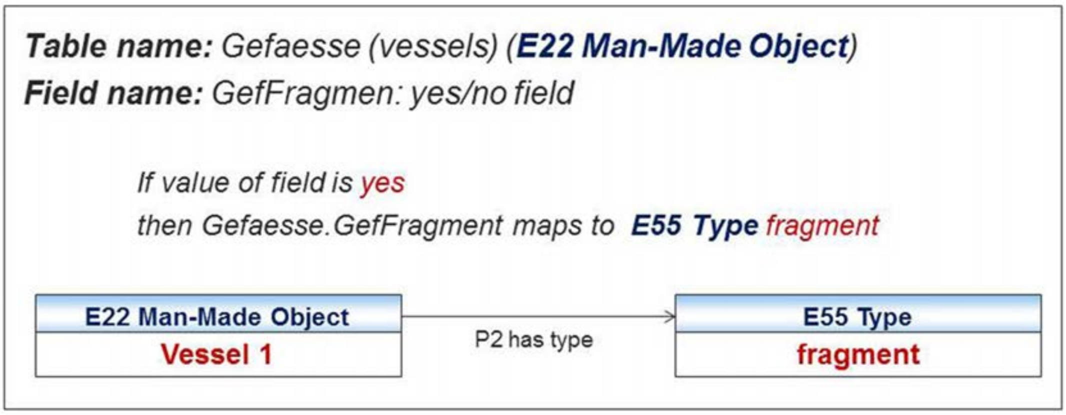

Figure 4. Yes/No fields.

a language attribute. The use of the **E41 Appellation** class is required only if there is need to assign some additional properties to the Appellation such as properties of use or attribution.

Instances of **E41 Appellation** '*are cultural constructs; as such, they have a context, a history, and a use in time and space by some group of users.*' and thus **E41 Appellation** is appropriate for historical names.

Common database fields: Yes/No fields

Yes/No fields are quite common in relational databases. These are typically mapped to types in CRM. For example, in a database about graves, we encounter the table 'Gefaesse' (vessels) and a boolean field named 'GefFragmen' that indicates if the vessel is a fragment or not. Figure 4: Yes/No fields presents the relevant mapping to a type, using an 'if condition' check to assign a 'fragment' typology to the vessel instance or not.

Common database fields: implicit and contextual information

It is quite often the case in current database management systems to have semantics expressed not on the data fields, but directly in the User Interface, in queries, or in the values of identifiers. Even worse, important semantic distinctions relevant to the correct understanding of the data in the database often exist only in the minds of the curators of this data. During the semantic transformation process, such information needs to be elicited and then made explicit in the outcome. For example, as shown in Figure 5: Revealing implicit and contextual information, we explicitly assign the units and types of measurements that were not stored individually with the source database records.

Additionally, when a local system is mapped with the intention of aggregating it with other local databases, additional context information, not directly modelled in the source, might need to be generated. For instance, all the implicit constants, the common context information of the database, can be added as explicit constant node information, under a suitable relation and class type. For example, though not explicitly in the records, every coin of the OEAW coin database is, in fact, currently under the custody of the OAEW. Thus, in an aggregated environment, it would be important to identify this custodial function using the property *P50 has current keeper* and adding the constant node **E40 Legal Body** 'OEAW' as shown in Figure 5.

Common database fields: categorical vs factual information

Quite often databases include both categorical and factual data. Incorrectly mapping these different levels will create inconsistencies. For example, in a coin database, the Find spot refers to a specific coin while the historical facts refer to a category of coins. Good examples and practice for modelling such data can be seen in the FRBRoo formal ontology which, *inter alia*, models the semantics of industrial publication processes in bibliographic information. Initially, the core model of CRM did not support categorical information. However, recently, the class **E99 Product Type** and the property *P186 produced thing of product type (is produced by)* have been introduced and will be included in the new version of the model (see Figure 6).

People: groups, nationality, origins

Information pertaining to individuals' belonging to various human social structures and relations to various topoi can be hard to disambiguate and model. Nevertheless, CRM classes can generally be used to help clarify what is meant by attaching labels like

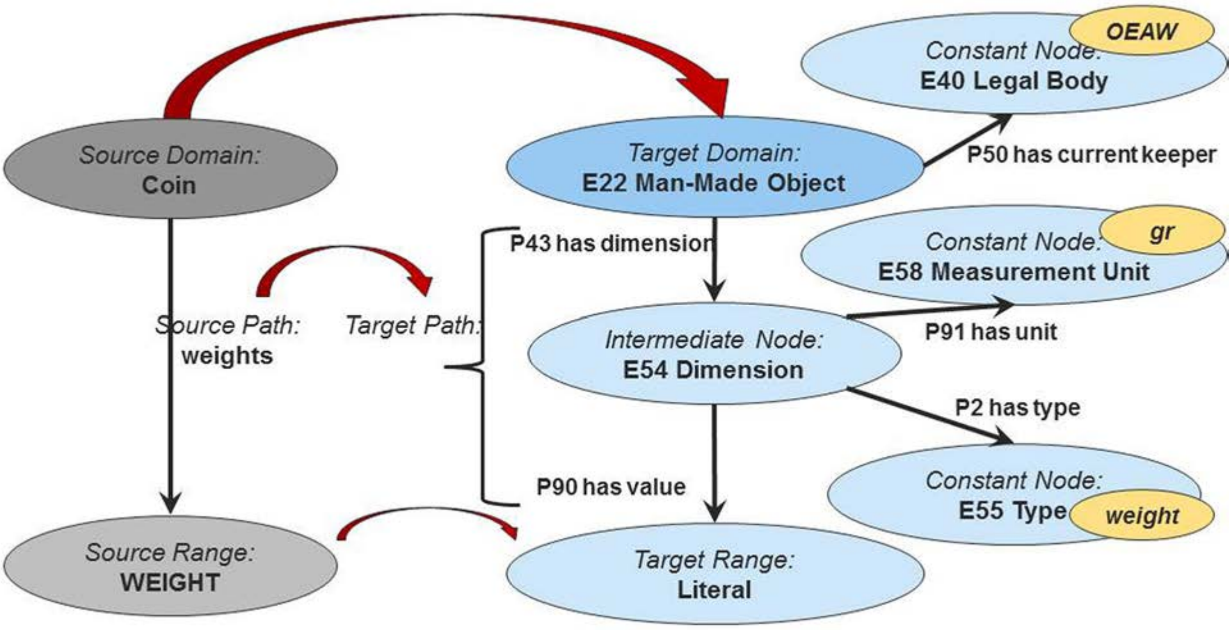

Figure 5. Revealing implicit and contextual information.

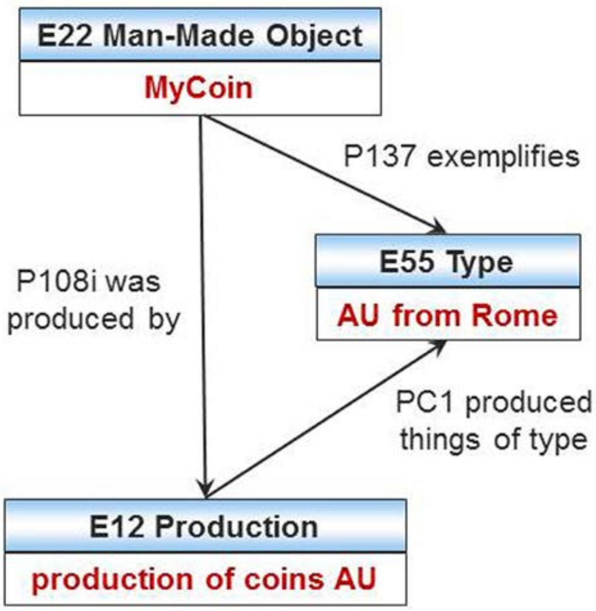

Figure 6. Modelling categorical information for coins.

'nationality' to individuals. Specifically, one normally finds some variant of the following possibilities:

- **Membership in an E74 Group**: suitable to model citizenship or social participation. An actor may join and/or leave the group (former, current member)
- **E67 Birth**: suitable to model origin/provenance
- **E55 Type**: suitable to model behaviour and ambiguous, fuzzy characterisations

In 2010, in the description of the painting *The Assumption of the Virgin* in the Art Institute of Chicago,[9] the painter of the work, El Greco, was indicated to be Spanish, as having been born in Greece and to have signed his works in Greek as 'Cretan'. In 2016, the description for the same painting states that El Greco is Greek and active in Spain. In CRM all this information can be analysed in detail as shown in Figure 7: Information in the description of an artwork at Art Institute Chicago. Spanish refers to the style of his painting, Greece is the place where he was born and more specifically in Crete and that he regarded himself as Cretan.

People: Accidental roles

Accidental roles are roles that do not characterise an actor independently from a particular context of activity. As modelled in the CRM, such roles can be captured through the property of the *P14.1 in the role of* which is a property on the property *P14 carried out* (see Figure 8). The property of property notion, however, cannot be represented in RDF. Quite often, in the attempt to overcome the RDF restriction, CRM implementers are tempted to assign these roles directly to the actor. Such an approach is wrong both because

[9] http://www.artic.edu/aic/collections/artwork/87479 (accessed in 2010 and in 2016).

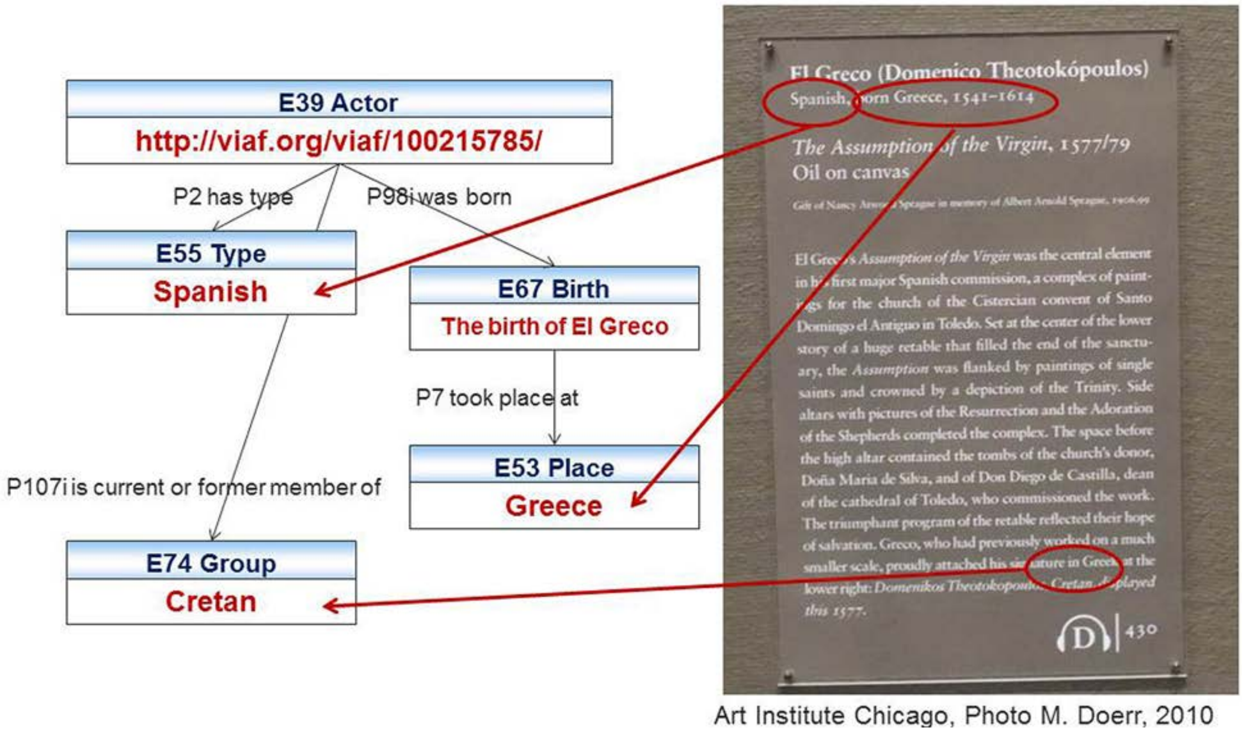

Figure 7. Information in the description of an artwork at Art Institute Chicago.

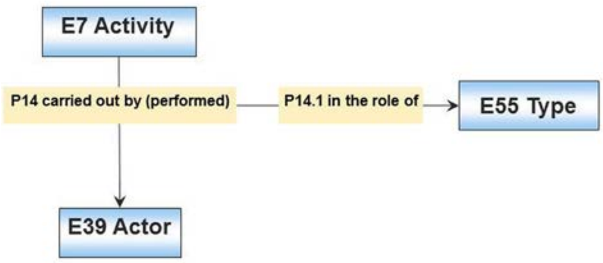

Figure 8. Properties of properties.

the context of the role is lost and because the actor is incorrectly characterised essentially by what was an accidental role.

For modellers facing this problem, we propose four possible ways to overcome the RDF encoding limitations, depending on their particular scenario:

Solution 1: The property *P14 carried out* can be specialised for each role (see Figure 9). This approach is the most efficient in terms of performance and is suitable when the set of possible values for the roles is known *a priori* and limited in size.

Solution 2: We introduce a new class **PC0 Typed CRM Property** and its subclass **PC14 carried out by** with properties *P01 has domain* and *P02 has range* (Figure 10). The equivalence of this solution to the original CRM definition is depicted in Figure 11. This solution has performance drawbacks on current triplestore implementations, but satisfies the problem of uncontrolled, a priori unknown, vocabulary of roles. Solution 2 is generic and is applied to all the properties of properties defined in CIDOC CRM. It is adapted by the CRM SIG for the RDF implementations of the ontology.

Solution 3: We add a note to each activity that describes the person's role. This approach is simple and does not require any extension to the model (Figure 12). It is adequate if no queries are expected specifying roles in the WHERE clause and is recommended in this case because of its simplicity and performance.

Solution 4: Instead of assigning a role to the actor, we assign a type to the activity that implies the role (Figure 13). As in the previous solution, an extension of the model is not required. This solution is adequate if no differentiation between involved actors is known or specified.

People: Political office

Political office is another tricky relation for first time modellers to address. Political office is best modelled as instances of **E74 Group** which, as it happens, will normally only have one member at any one time. Actors joining and/or leaving the group (former or current

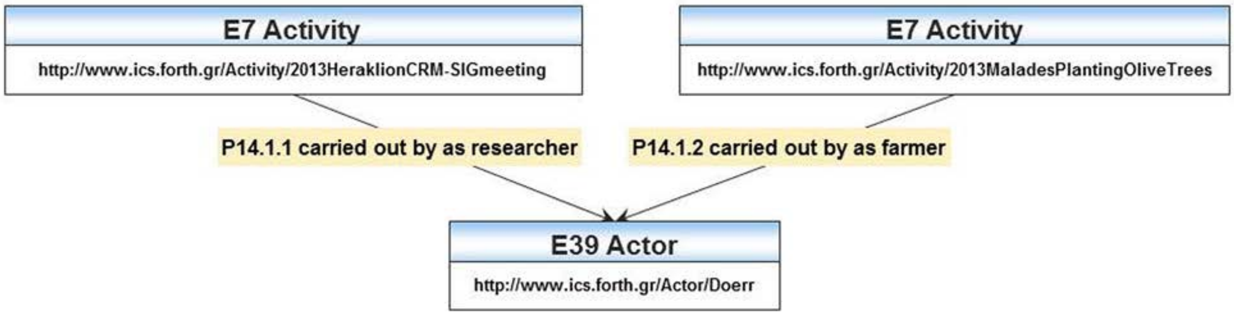

Figure 9. Solution 1 — Specialising *P14 carried out by.*

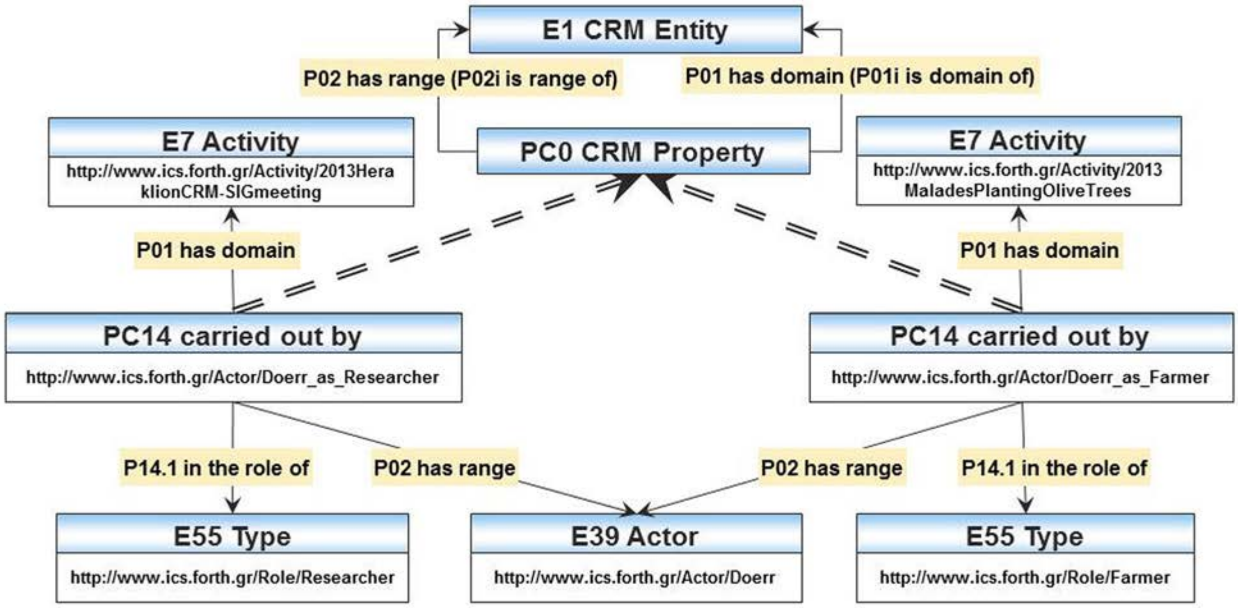

Figure 10. Solution 2 — Extending the model.

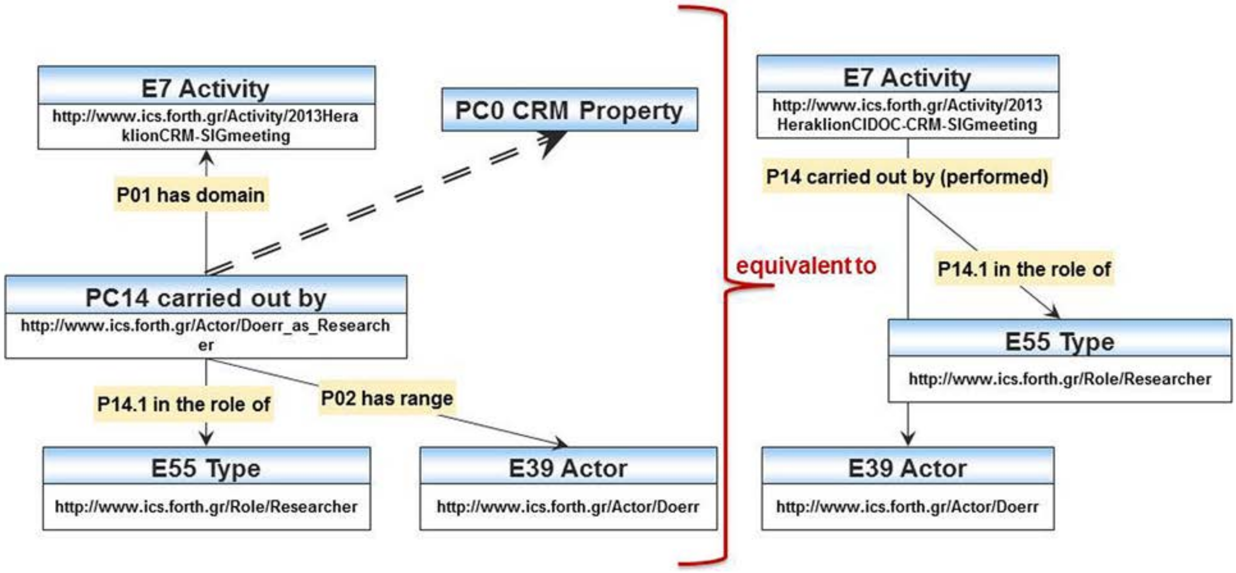

Figure 11. Solution 2 — Equivalence to the CRM definition.

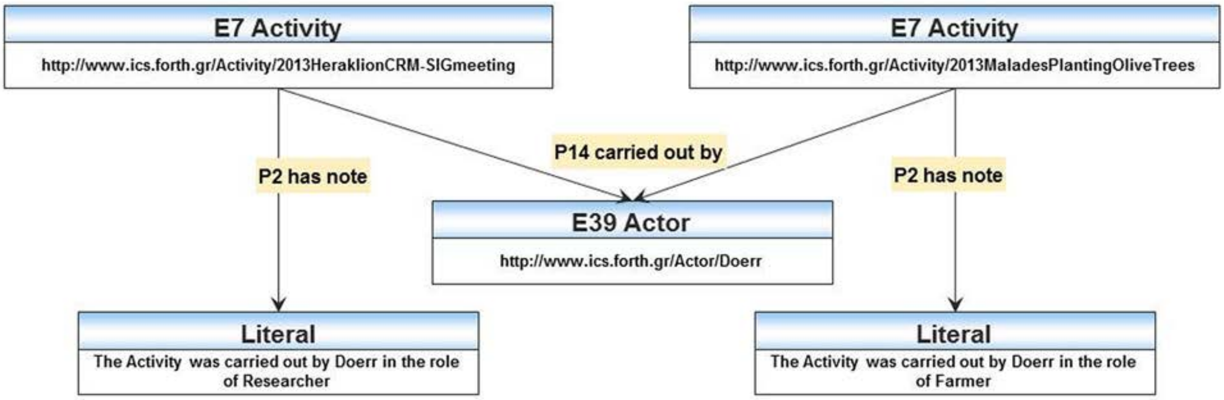

Figure 12. Solution 3 — Describe roles in activity notes.

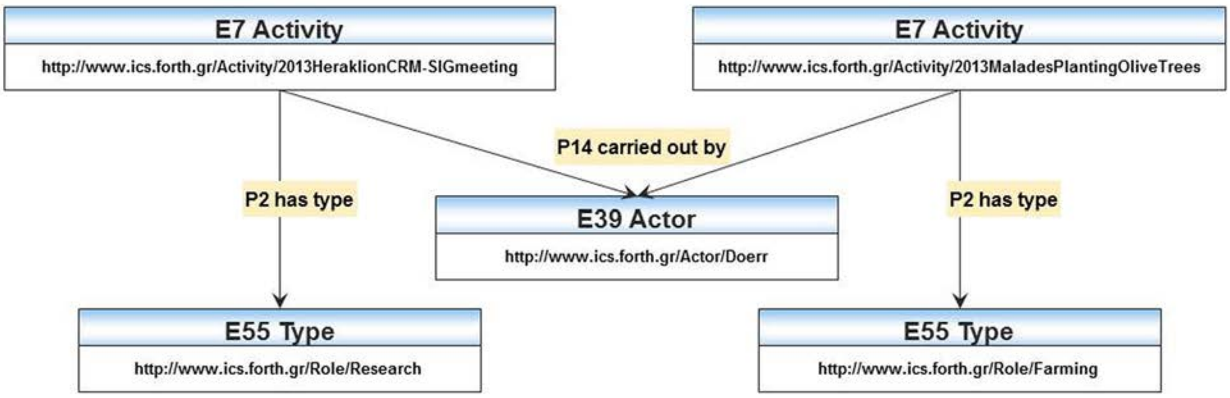

Figure 13. Solution 4 — Typing the activity.

members) create the history of the office. For example, Alexis Tsipras[10] is the 185th and current Prime Minister of Greece, having been sworn in on 21 September 2015. He previously served as the 183rd Prime Minister of Greece from 26 January 2015 to 27 August 2015 when he resigned and called for election. Vassiliki Thanou-Christophilou was appointed as an interim Prime Minister until elections were held. This information can be modelled as:

E74 Group *The Prime Minister of Greece*

P144i gained member by ***E85 Joining*** *P143 joined* ***E39 Actor*** *Alexis Tsipras*
P4 has time-span ***E52 Time-Span*** *26 January 2015*
P146i lost member by ***E86 Leaving*** *P145 separated* ***E39 Actor*** *Alexis Tsipras*
P4 has time-span ***E52 Time-Span*** *27 August 2015*
P144i gained member by ***E85 Joining*** *P143 joined* ***E39 Actor*** *Vassiliki Thanou*
P4 has time-span ***E52 Time-Span*** *27 August 2015*
P146i lost member by ***E86 Leaving*** *P145 separated* ***E39 Actor*** *Vassiliki Thanou*
P4 has time-span ***E52 Time-Span*** *21 September 2015*
P144i gained member by ***E85 Joining*** *P143 joined* ***E39 Actor*** *Alexis Tsipras*
P4 has time-span ***E52 Time-Span*** *21 September 2015*

Places: countries

Because of the geographical and historical evolution that countries are subject to, they can present particular difficulties to semantically model correctly. Generally, the best way to accurately capture the proper intention of a country is to map it, along with all other referenced geopolitical units as an instance of **E4 Period**, typing it as 'State', 'City', etc.

Countries can also be mapped as instances of **E53 Place,** but in this case the identifier of the place should encode both the name of the country and the date

[10] https://en.wikipedia.org/wiki/Alexis_Tsipras

that indicates the validity of the name. In so doing, we create a snapshot that allows the proper understanding of the historical and geographic extent referenced by a country appellation.

In either case, it is important to refer to a global authority when assigning the identifier e.g. TGN. This helps not only in compatibility and retrieval, but also enables automated reasoning with regards to a series of properties such as *P10 falls within*, *P121 overlaps with*, *P132 overlaps with* and *P1 is identified by*.

Places: fictional places

In many data sets, fictional places are referenced. It is a temptation for first time modellers, to make these instances of **E53 Place**. **E53 Place**, however, always and only represents **real** extents in space independent of time and is not suitable to represent a fictional place which has no real extent. Fictional places are not places at all, but formulated ideas, that be represented as instances of **E89 Propositional Object.** The ambiguity that seems to hang between real and fictional places is an ambiguity introduced by data structures and does not actually exist in the mind of the researcher. The researcher might literally try to go to Canada. They would not literally try to go to hell.

If we take 'hell' as our leading example, we can see that there are many different formulations of the concept of hell available in different cultures (Figure 14). None of these are places per se, but are rather formulations of a notion of an unpleasant afterlife. In many cultures, hell was conceptualised as having some connection to a topos in a physical world. Therefore, we end up with some variant of a concept for 'hell' that has some real world geographic place referent. All of this can be distinctly modelled, without confusing ideas for places or places for ideas, as seen in Figures 15 and 16. Since recall is preferred over precision, providing explicitly several alternatives improves query capabilities.

Pieces of a broken object

Another common situation encountered in artefact oriented databases is related to the problem of broken pieces and how to capture their relation to an original, whole vessel. There is a temptation to give the relation to the broken vessel though a part of relation like *P46 forms part of*. This is nonsensical, however, since the broken piece is precisely no longer part of the whole vessel. Rather, pieces of a broken object should be mapped as products of an event that destroyed the object (see Figure 17). This modelling approach preserves the provenance information, relating the piece to the whole, and is semantically clearer since the respective pieces of matter were not distinct and had no identity prior to the object's destruction.

Destruction in this context denotes the end of the period that the object is usable. If this is not the case, the fragment could be described as being the result of a process of **S1 Matter Removal** (CRMsci).

Figure 14. Different views of Hell.

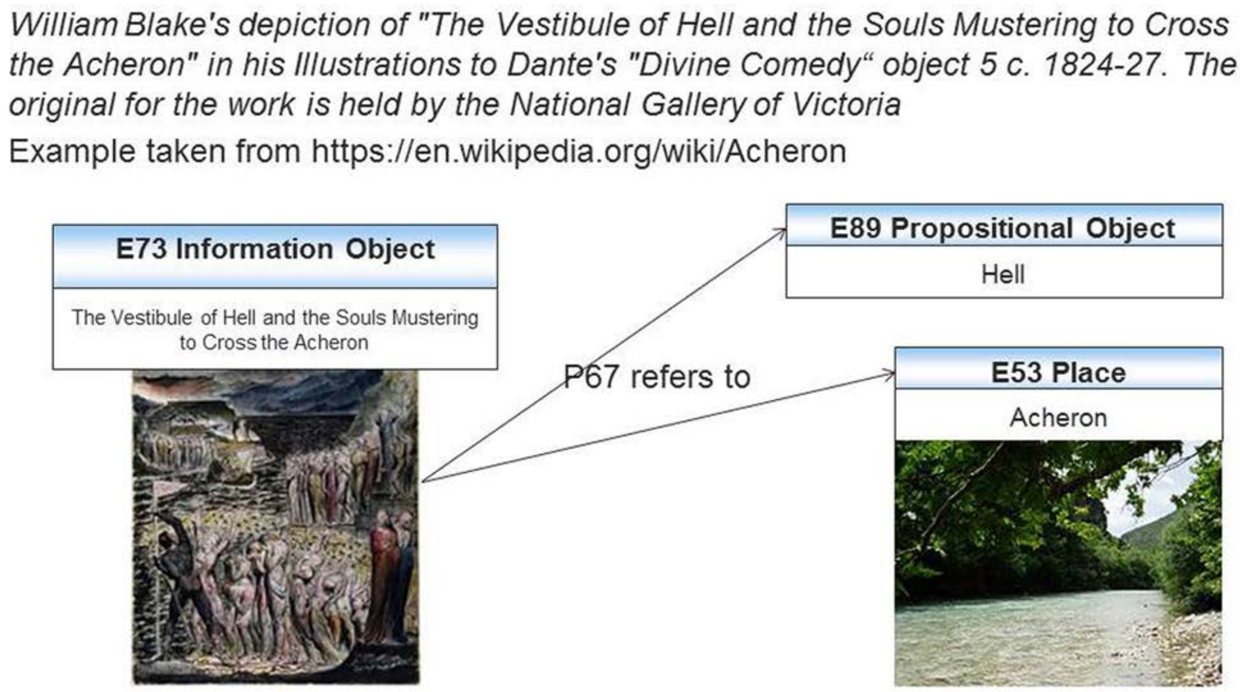

Figure 15. Modelling Hell.

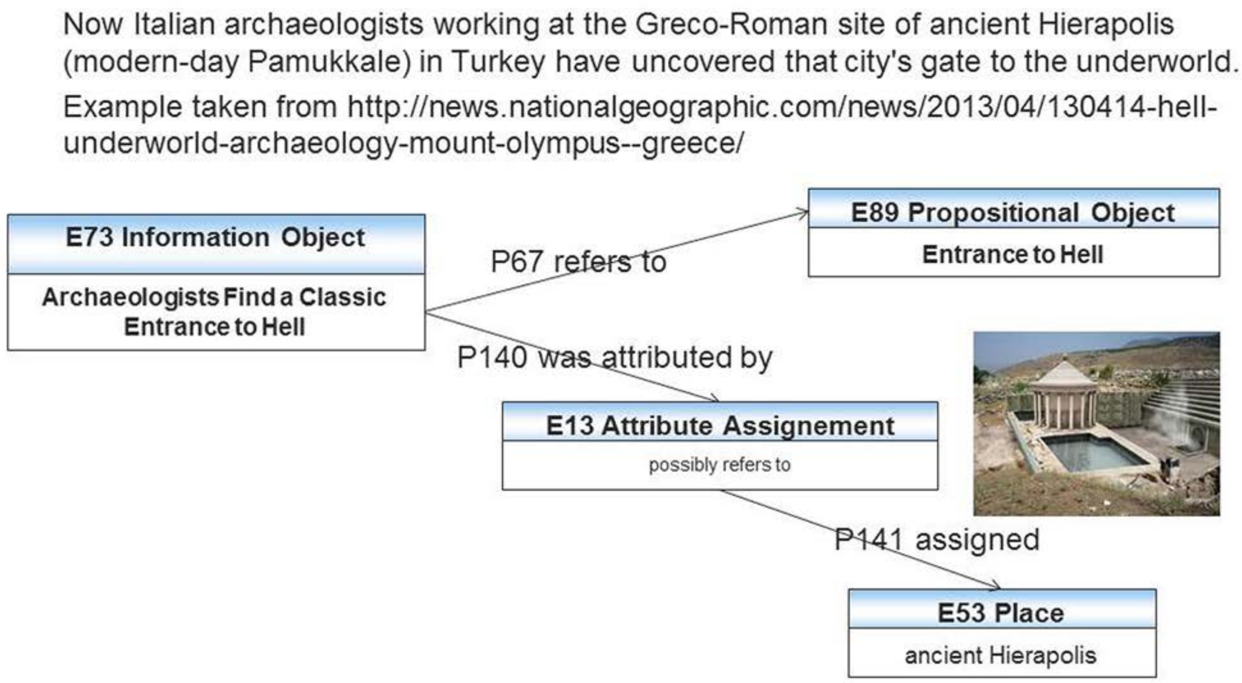

Figure 16. Modelling the Entrance to Hell.

Pieces of a set

Pieces of a set are mapped as parts of the whole object. For example, a chess set has as parts the chess board and the chess pieces as shown in Figure 18. The level of decomposition necessary is at the discretion of the documenter and their needs for tracking parts.

Aggregate objects in general, like a tomb full of gifts, a folder with stamps or a set of chess-pieces should be

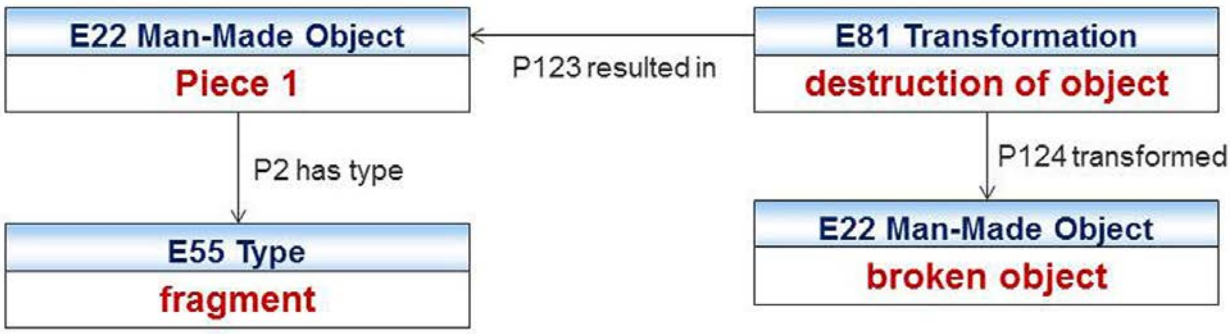

Figure 17. Pieces of a broken object.

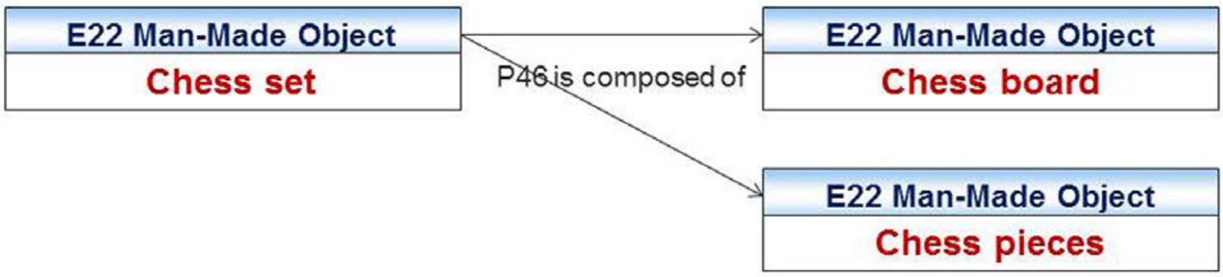

Figure 18. Pieces of a set.

documented as instances of **E19 Physical Object**, and not as instances of **E78 Curated Holding**. **E78 Curated Holding** plays the specific role in CRM of describing objects that are held together as a collective through an active process of curation. Aggregate objects, however, are not together because of some agency keeping them together as a whole, but rather because they are physically bound together in a relative proximity (folder with stamps) or because they are kept together for their functionality (chess set).

Conclusions

This paper aimed to help the reader gain a better understanding of the mapping process as such, how to select and read an ontology for a target schema in order to understand how to apply it, and learn a number of practical tips on common modelling problems faced by first time data mappers using CIDOC CRM.

In the context of our research currently we work on mappings from XML schemata to the CIDOC CRM RDF encoding. However, the mapping process is independent from a specific encoding paradigm and follows the same principles for all transitions between relational, XML and RDF schemata.

Acknowledgements

This work has been conducted as part of the ARIADNE, FP7-INFRASTRUCTURES-2012-1 EU project (Grant agreement no: 313193).

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Mieko Matsumoto and Espen Uleberg (eds) 2018. ***CAA2016: Oceans of Data***
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
Oxford: Archaeopress

An Ontology for a Numismatic Island with Bridges to Others

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Abstract
Nomisma.org is a collaborative project to provide stable digital representations of numismatic concepts according to the principles of Linked Open Data. These take the form of http URIs that also provide access to machine-readable information about those concepts, along with links to other resources. We have also constructed an ontology for representing concepts in our thesaurus, and this has been applied to digital representations of physical specimens, enabling linking between specimens in Nomisma-defined numismatic concepts. Although this paper does not describe the ontology that was generated itself, it does describe our process and decisions in designing it in order to allow the highest possible flexibility, and therefore to reduce the barriers in using it. It further shows how different services within the numismatic domain use Nomisma.org and its ontology to link between each other. We see various bridging dimensions that also allow links to other domains, but there is still work to be done before we can call them stable.

Keywords: ontology, modelling, social challenges

Introduction

As a mass-produced medium, coinage provides an excellent testbed for the implementation of Linked Open Data (LOD) (Berners-Lee, 2006). Nomisma.org was initiated by a group of numismatists and IT experts in 2010 in order to provide discipline-specific and stable digital representations of numismatic concepts to facilitate the application of LOD. These representations take the form of http URIs that promote interoperability between numismatic resources by providing access to reusable information about the concepts, as well as links to and from other fields of the study.

To date the project has mainly concentrated on the coinage of the ancient world, with great advances being made, and a number of web resources based on Nomisma.org now link extensive data sets on the coinage of the Roman Republic and Empire, as well as on individual coinages of the Greek world, from a variety of sources. At the date of writing, over 200,000 physical specimens from 23 institutions are linked to online type corpora driven by Nomisma.org.

Current plans and ongoing projects comprise, on the one hand, expansion within the domain of ancient numismatics such as the initiation of further type corpora for Greek coinages, as well as implementation in other fields of numismatics, including Islamic and Medieval. On the other hand, Nomisma.org is not intended as an isolated 'island', but to be fully integrated into the world of LOD. For example, many of the coins linked to Nomisma.org are coin finds, and as such are part of the archaeological domain, so that a bridge between the two domains is necessary for data on them to reach its full potential.

The discipline of numismatics was one of the driving forces behind academic advances in the Age of Enlightenment, and coinages are today a potent source of information for a wide range of disciplines both within the humanities and the natural sciences, from art history to metallurgy. The Semantic Web provides unprecedented opportunities of leveraging numismatic data to a wide range of communities to an extent never seen before.

The nomisma.org ontology creation

No ontology existed that was able to cope with the level of granularity and the precise domain specification as needed by numismatic experts to exchange their data and to work on research questions. Of course more general ontologies existed, but they lacked the specific concepts needed in the domain. Reusing and adopting existing ones was therefore not possible for the core elements.

Nomisma.org started more like a domain thesaurus. All concepts were kept in one single namespace (we call it id namespace — under: http://nomisma.org/id/)and no explicit ontology was created for defining the containing concepts. The special features needed in order to express 'somebody is an issuer of a coin', for example, were simply introduced by defining an *issuer* concept. Such concepts were used in various ways, mixed in a class and property style, and therefore everything was extremely open and flexible. However, over time the number of concepts grew and it became obvious that some structure was needed in order to be able to handle and maintain them. Therefore, the Nomisma.org steering committee collaborated over a series of conference calls and took the decisions: a) to move some data to extra areas (for example the descriptions of coin types, or the URIs of a number of Greek coin hoards that had been included originally) that are specific to particular fields of numismatics, and b) to create an ontology in which we define at an upper level the specific classes and properties we see as mandatory for the numismatic area. As a result, hybrid usage (such as class and property) was no longer accepted. However, the process of creating this ontology as a group distributed over Europe and the USA discussing the pro and cons of different aspects was a time-consuming process, and it took nearly a year before we published a first version early in 2015.

Two main challenges had to be handled during the creation of the ontology: a) which **level of detail** did we want to cover for the numismatic domain, and b) did we **need to create** a certain class or property for the numismatic domain, or could we reuse existing ontologies without losing any semantics?

Level of detail: As probably in any domain, experts may have different viewpoints. In numismatics there are differences depending not only on the period and area under consideration (e.g. Roman, Greek, Modern), but also what kind of material is in focus, for example coin finds (being potentially in very bad condition), where the archaeological context is of great importance, or coins as individual objects (for example, to create typologies or for die studies), in which case descriptive data is of the essence. Both areas are important and they are interdependent. The ontology should work for both, but without increasing the number of properties and classes to a level where the complexity gets too great, and as a result the ontology will no longer be usable. At present the ontology is used by different institutions, including some that are not represented on the steering committee, and to date there has not been any negative feedback.

Do we need to create it? We did not intend to reinvent the wheel. Our approach was to look for existing ontologies to see whether any could be used to describe numismatic concepts. This reuse of ontologies is sometimes referred to as *ontology hijacking*, a description which does, however, imply a negative view of the practice that we do not share. However, for us this is exactly how linked open data should work. If everybody generates their own, closed ontology, without reusing existing and known concepts, the result would simply be a mess. Of course, one can link one's own properties and classes with *owl:sameAs* or *skos:exactMatch*, which is then understandable by computers. But for humans it is quite demanding to have to remember all of the links, which creates a barrier for acceptance.

For the definition and description of Nomisma.org concepts we therefore currently reuse elements from various ontologies. In particular for persons, such as issuing authorities, or simply persons that are displayed on a coin, there was no need to create a new class. The friend of a friend ontology (Brickley and Miller, 2014), which was first issued in 2000, is well known, and we use its person class. For details that cannot be expressed within it, such as the death of a person, we use BIO (Davis and Galbraith, 2003). Many persons had a wide range of different positions and roles. Domitian was Roman emperor from AD 81 to 96, however coins bearing his portrait were already issued under Titus.[1] In order to reflect different roles, even roles running concurrently, we use the role concept based on the organisation ontology specified by the World Wide Web Consortium (Reynolds, 2014). This means that when we talk about Domitian as a person, we simply refer to: http://nomisma.org/id/domitian, while if we mean Domitian in his role as a Roman emperor we refer to: http://nomisma.org/id/domitian#roman_emperor.

We also use CIDOC-CRM (Crofts *et al.*, 2011), at the moment mainly for periods (*crm:E4_Period*). Additional usage of CIDOC-CRM vocabulary is planned, since it is important within the archaeological domain and thus more intensive usage would simplify interoperability.

Another very important issue we are working on is uncertainty. Uncertainty can be found in nearly every issue within archaeology, which is no wonder when it comes to reconstructing history after thousands of years based only on a limited number of finds and sources. In order to express uncertainty, we use the ontology described in the W3C report Uncertainty Reasoning for the World Wide Web (Laskey *et al.*, 2008). More details on how to model uncertainty can be found in Tolle and Wigg-Wolf (2015).

A further design goal for the ontology was to provide users with the freedom to model things in their own way. The reason behind this is that our experience showed that it is much easier to convince people to use a linked open data approach when they are able to model it in a way they are used to. We therefore, after a long discussion, decided to avoid any *rdf:range* or *rdf:domain*

[1] e.g. http://numismatics.org/ocre/id/ric.2_1(2).tit.86

definitions for the properties within the Nomisma.org ontology, meaning the subjects and objects used with our properties do not have to be of certain classes, nor will they automatically be instantiated into such. This way the ontology can be used outside Nomisma.org in different ways. Of course, within Nomisma.org we follow our own modelling, and for those who want to submit their data sets to it we have introduced a standardised way to use the ontology to describe a coin. This is further explained online under the 'How to contribute' section (Nomisma.org, n.d. b). It must be stated, however, that this freedom can cause interoperability problems. Even if two projects use the Nomisma.org ontology, different modelling can complicate the integration of the data from them. However, we assume that the Nomisma.org ontology will not be used on its own. Users will 'hijack' it (as we did others!), and if we were to enforce specific modelling, or had domain and range definitions, it would be less straight-forward to use it elsewhere.

In contrast, a very different approach has been taken by CIDOC-CRM, where the way to model is integrated into the standard (event-based modelling), and all properties do have range and domain definitions. The goal of CIDOC-CRM is to leverage interoperability and therefore, these constraints are necessary! It should also be stressed that no problems are foreseen in combining CIDOC-CRM and Nomisma.org. As mentioned above, Nomisma.org already uses some elements in CIDOC-CRM for describing numismatic concepts. In a similar manner, it is also possible to define Nomisma.org properties as subproperties of existing properties of CIDOC-CRM (in this case the range and domain of the superproperty would be inherited to the subproperty), and to use the appropriate modelling approaches.

Usage of the nomisma.org ontology

As mentioned above, projects can provide their coin descriptions using the Nomisma.org ontology and the modelling described under (Nomisma.org, n.d. b). These data sets are published in a list on the Nomisma.org website. Currently, there are data sets from 23 institutions containing more than 200,000 descriptions of coins, coin types and finds of various kinds. These data sets are used within Nomisma.org. When you open the id for an authority that issued coins that are contained in these data sets, a selection of them is displayed as examples.

For certain fields of numismatics, there are existing typologies that are widely accepted. This is especially true for the Roman Imperial Coinage and the Roman Republic Coinage, as well as for the coins issued in the name of Alexander the Great. For these, there are already online digital type corpora, namely: OCRE (Nomisma.org, n.d. c), a digital type corpus based on Roman Imperial Coinage (RIC), CRRO (Nomisma.org, n.d. a), and PELLA (Nomisma.org, n.d. d) for the coinage of Alexander. All these online resources use the Nomisma.org ontology, and make use of the data sets submitted to Nomisma.org. Where a coin from one of these data sets is linked to a specific coin type in one of the typologies, it is listed in OCRE, etc. as an example of the type. This has various benefits:

1. for the coins that are linked with an image, the image is retrieved from its original source (most probably the institution that submitted the data set); the **user** now has the benefit of seeing the different images, which can help them to identify a coin type, but the **institution** that has contributed the coin data also has the profit that it can see in its log-file how often an image was accessed via the site.
   In addition, the user can directly follow the link to the institution should they be interested in a specific specimen and want to access more details. In this way the sites that use the Nomisma.org ontology can be seen as promotion areas for the institutions contributing data.
2. for those coins that have the location of the find spot defined, the find spot (as well as the position of the relevant mint) is visualized in a map under OCRE, etc., as shown in Figure 2. This means a user can see the distribution of specific coin types from various institutions in one view (without integrating the data manually). In addition, the link to the find spot of the coin in the original source is provided. In the case illustrated here, it is the system of the Römisch Germanischen Kommission (RGK) (2017) using a system called Antike Fundmünzen in Europa (AFE). By following the link to Wetzlar-Niedergirmes in the figure, a list of other coins that were found at the same location is accessed.

Bridges to others

When it comes to answering archaeological research questions, sooner or later something called archaeological context is encountered. But the problem with context is that there are no clear borders, and, what is more, the different types of objects that are found by archaeologists are themselves complex. This is why some archaeologists are experts for weapons, while others are experts for ceramics, and yet others for coins. Other archaeologists, again, do not concentrate on single object types, but rather on specific periods and/or on regions. In short: nobody knows everything.

A central goal of ontologies is to allow cross-links to others and to provide ways of setting relationships. In numismatics, the level of detail when dealing with coins

Figure 1. Examples of coins of the type Vespasian 777 in RIC 2nd edition, from Valencia and Berlin as displayed under OCRE.

is very fine and granular, but whilst linking different areas on such a fine granular level might be desirable, it is also very difficult. However, in our view there are a number of bridging dimensions that are present in most specialised archaeological domains. These are:

- Places
- Persons and organisations
- Time
- Literature
- Material

It is therefore important to provide links from the fine granular numismatic concepts we define, to more general, higher level definitions. In order to do so, we mainly use SKOS (Miles and Bechhofer, 2009) properties like *broader*, *closeMatch*, *exactMatch*. Currently we connect from Nomisma.org to: Getty, Dbpedia, Wikidata, Europeana-EAGLE project, Viaf, Pelagios / Pleiades, Geonames, and others. The links are either automatically generated or included manually.

The institutions that provide their data, in many cases have additional connections. For example, AFE provides links to the iDAI.welt (Deutsches Archäologisches Institut, n.d. c). This makes sense, since AFE is used and initiated by the RGK as part of the Deutsches Archäologisches Institut (DAI). Find spots and bibliographic references within AFE are linked to the iDAI.gazetteer (Deutsches Archäologisches Institut, n.d. b) and Zenon (Deutsches Archäologisches

Figure 2. Find spot shown in a map under OCRE. Here for a specimen of the type Vespasian 777 in RIC 2nd edition recorded in the AFE system of the RGK.

Institut, n.d. a) respectively. For the find spot of Wetzlar-Niedergirmes for example, AFE provides a list of bibliographic references and of objects from the iDAI.welt (not only coins), as shown in Figure 3. Since ultimately the data from the different sources builds one huge graph, this can also be useful for linking the data from other sources, or data of different kinds, with each other.

This might sound easy at first. However, the practical level here is formidable. One of the main challenges we

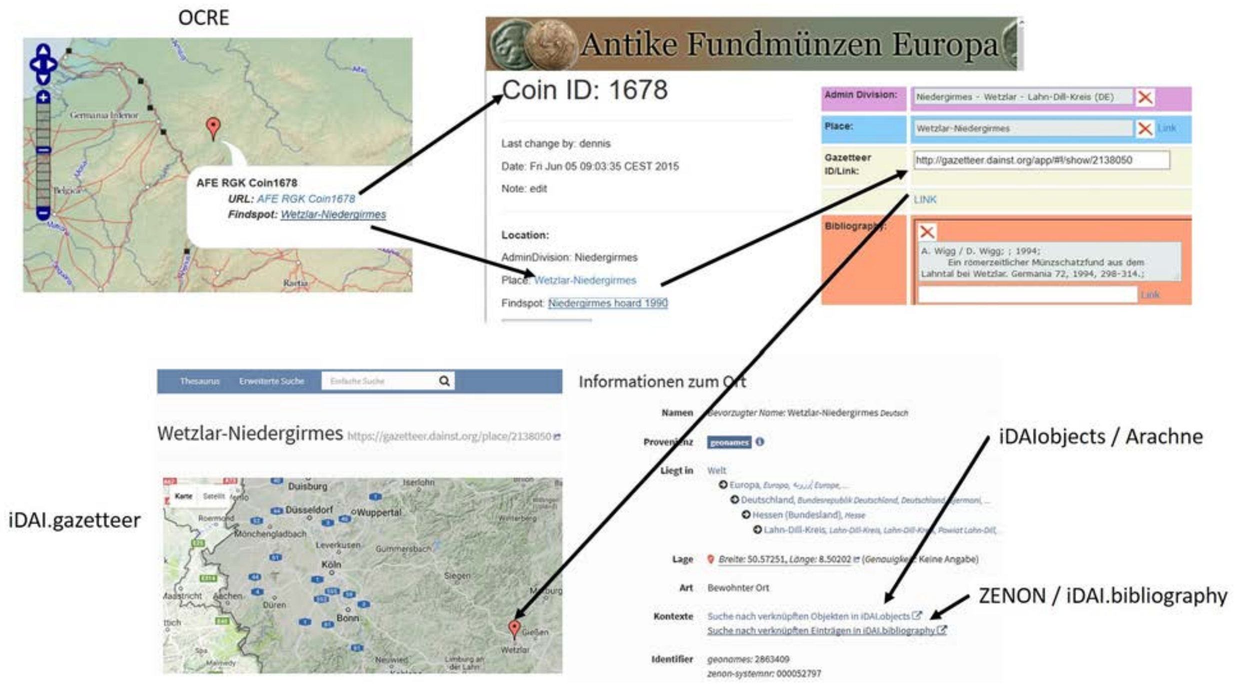

Figure 3. Starting from the coin or find spot in OCRE one can navigate to the providing institute (here RGK/AFE) which is further connected to iDAI.welt.

see is presented by the different granularities and levels of hierarchy. The bridging dimensions mentioned above are interleaved, and do not necessarily correspond exactly to each other. The time span of the Roman Empire within Britain is different to that elsewhere. In a conference call, for example, we were discussing the problem of how many concepts we should generate for mints at the place Istanbul/Constantinople/Byzantium? Some suggested that we should have just one concept, but since we all agreed that semantically these mints are different, even if their geoposition is more or less identical, in the end we chose to generate all three concepts. And of course, if you drill down into more detail at a finer, more granular level, you could generate many more concepts. So, we are again fighting with the level of detail.

How data sets are managed

As mentioned, data sets that are provided by institutions need to follow the way of modelling as described under (Nomisma.org, n.d. b). In addition to the semantic modelling, it is stipulated that for each data set dump there must be a file based on the VoID Vocabulary (Alexander *et al*., 2011). This file includes licence information and metadata about the institution and data set. Within the data set itself each element described should have in its description the property *void:inDataset* defined. This is used for updates in case a new data set is provided by the institute. In this case the previous elements can be identified and removed by this property, before the new data set is entered.

For some of the data sets that change more frequently, the system of Nomisma.org automatically recognises this by periodically checking relevant URLs for updates. Newly available data sets or changes of institutes that do not update very frequently are handled manually at the moment.

Since the data sets are provided by different institutions, there may be differences between them. For example, the Nomisma.org ontology allows a coin to have a minimum and a maximum diameter, but not every database contains this level of granularity, and some might just have one diameter value. Also, the data quality of the different sources is likely to be very different and in some cases we even have duplicates (where, for example, two institutions entered information on a coin find from literature). At the moment we are working on rules based on SWRL in order to identify inconsistencies across different data sets. Others are also working on this, and have even introduced a 7-star model, where the 7th star includes a data quality metric (Hyvönen *et al*., 2014).

Summary and conclusion

Creating an ontology is not easy, and depending on the situation, the rules for creating ontologies change! In our case the goal was only to generate the vocabulary, and not to enforce the grammar (the modelling). For this reason we avoided any constraints where possible, even in the definition of *rdf:range* or *rdf:domain* specifications for the properties we created.

The second goal was not to generate classes and properties that already exist and are not semantically bound to the numismatic world. This distinction was and is not easy, and for the descriptions of numismatic concepts this meant that we 'hijacked' a number of other ontologies in order to fill gaps.

We already link the numismatic concepts defined to other norm data and more general information sources, and are currently searching for use cases to prove our ideas on how to bridge to other archaeological fields in order to further prove the feasibility of our approach. As mentioned above, we expect that it will still be quite a challenge, since the bridging dimensions interfere with each other. In order to find an appropriate use case various conditions must be met: 1) the different data sets (from the field of numismatics and a further field) must be available, 2) both data sets should overlap in some of the bridging dimensions, 3) both need to link to the same norm data or general information sources and 4) there should be a useful or relevant research question that can be addressed by linking the two fields.

However, even without such a use case, we can already say that Nomisma.org and its ontology enables the field of numismatics to function as one island, and not as an unlinked archipelago. Furthermore, the process of generating the ontology and of discussion among the experts is, in our view, extremely fruitful, even mandatory. If people do not accept each other's viewpoints, the effect of standards and ontologies is very limited. This does not mean that every difference can and should be eliminated. The graph structure of RDF and the possibilities that are offered, including the possibility of modelling uncertainties, is powerful enough to reflect different viewpoints.

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Mieko Matsumoto and Espen Uleberg (eds) 2018. *CAA2016: Oceans of Data*
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
Oxford: Archaeopress

Integrating Analytical with Digital Data in Archaeology: Towards a Multidisciplinary Ontological Solution. The Salamis Terracotta Statues Case-Study

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Abstract
Archaeological multidisciplinary research relies on heterogeneous data types (measurements, spectra, etc.), while what is commonly published is the integrated interpretation of such data. A major task is to create a virtual environment where primary, processed and interpreted data are archived and available for interrogation. Such a task must rely on a knowledge management system that captures how data was acquired and produced (the scientific process of measurements, data acquisition, mathematical operations, etc.) along with its derived interpretation and reasoning process, ending with conclusions. This is essential for any scientific process where data transparency is the only mechanism for the verification of results, conclusions and duplication of experiments.
The paper presents the first results of an ongoing research partially funded by the EU projects ARIADNE and GRAVITATE, based on the integration of archaeological, geometrical and chemical data collected during the analysis of terracotta statues fragments from the Salamis–Toumba archaeological site in Cyprus.

Keywords: formal knowledge representation, heterogeneous data, data transparency, ontologies

Introduction

Multidisciplinary research produces heterogeneous data types, such as chemical or geometrical measurements, alpha-numeric data, images, etc. Consequently, such data is processed, interpreted and conclusions are drawn and published. Primary data is seldom published in its entirety, what is being presented to the scientific community is usually processed data. From a data transparency perspective, the desirable solution is to make available for consultation the entire corpus of the data-cycle, described through appropriate metadata and paradata. A key challenge is therefore the integration of archaeological, analytical and digital data into a virtual environment based on a semantic-based archiving system which is open for consultation.

A large part of the European Cultural Heritage has its counterpart in digital format (virtual museums, digital libraries, scientific repositories) and this requires a huge effort for the management, preservation and archiving of such assets. To be able to retrieve information from repositories, data have to be well structured, preferably adhering to common documentation standards[1] or ontologies. The integration and organisation according to a rich, cross-domain metadata and to a standard conceptual reference model (CIDOC-CRM) helps to establish a multidisciplinary research infrastructure.

Integrating data from multidisciplinary research

Archaeological digital data sets are nowadays available through various sources online; the use of diverse technologies and tools to acquire and post-process data produced further increases the heterogeneity of data and thus the requirement for proper documentation and archiving methods that capture such processes. This heterogeneity contributes to a high fragmentation of information, and as a consequence, in difficulty accessing data in an integrated way. The necessity is therefore to aggregate them in order to enhance the use and re-use of data through the interoperability of such digital archives. It is important to aim at the integration of different data pertaining to archaeology: not only archaeological data *tout court*, but also all the multidisciplinary data that comes with archaeological studies (e.g. analytical, digital, geological, etc.). Enhancing a shared and collaborative use of interdisciplinary archaeological data could resolve this fragmentation of data sets and data (Geser, 2014).

The challenge presented above is currently addressed by the research activities of the ARIADNE project.[2] Its

[1] Metadata is a structured information that describes, explains, locates, or otherwise makes it easier to retrieve, use, or manage an information resource. More comprehensively, it could be: 'Structured information about any kind of resource, which is used to identify, describe, manage or give access to that resource' (McKenna and De Loof, 2009).

[2] http://www.ariadne-infrastructure.eu/

main aim is to support new study and the re-use of data; unifying and integrating existing archaeological research data sets. The creation of a web-based service based on common interfaces to data repositories can guarantee transnational access for researchers to data centres, tools and guidance. The research activity described below relates to the integration within ARIADNE of the study of terracotta statues found at the Salamis–Toumba archaeological site (see below), performed within the EU funded project GRAVITATE.[3] The aim of this study is to characterise technological and technical traits of the production of such statues, their material and a typological/stylistic analysis based on 3D geometry and features characterisation.

The case study: the fragmented terracotta statues from Salamis (Cyprus)

The archaeological site of Salamis is located on the eastern coast of Cyprus. The site has a long history, starting from the XI century BC to the VII century AD when Arab invasions destroyed the site (Karageorghis, 1969). Southwards from the Roman remains, between two rivers, there is a small rocky hill called Τούμπα. The British Mission that excavated the site in 1890 interpreted it as a shrine (Munro *et al*., 1891). The large number of fragments of statues, made of terracotta or limestone, were found together with pottery and several other objects and interpreted as vows. Most statues represent male bearded figures. They are attributed to the Neo-Cypriote style, dated from the second half of the VII century BC to the early VI century BC (Karageorghis, 1993). Most fragments retain evidence of black and red decorations, a white-pinkish slip to imitate skin colour, while some have traces of yellow in the areas of jewellery.[4]

The collection counts numerous fragments dispersed in several museums and private collections around the world. Among these, ca 160 at the British Museum, ca 20 at the Ashmolean Museum, ca 12 at the Fitzwilliam Museum and 19 at the Cyprus Museum. Only a few items were studied and published (Munro *et al*., 1891), while others were given a stylistic description (Karageorghis, 1993). Since 2013 these fragments have been 3D documented, and their geometry analysed for possible virtual restoration; a physico-chemical analysis was performed on the artefacts conserved at the Cyprus Museum.

Analytical and digital data

Nineteen fragments, stored at the Cyprus Museum in Nicosia, have been 3D documented and their physico-chemical properties measured. Data available and produced by our research are the following:

- Archaeological description

The archaeological items were described visually using traditional parameters and typologies, partially published in literature (Figure 1).

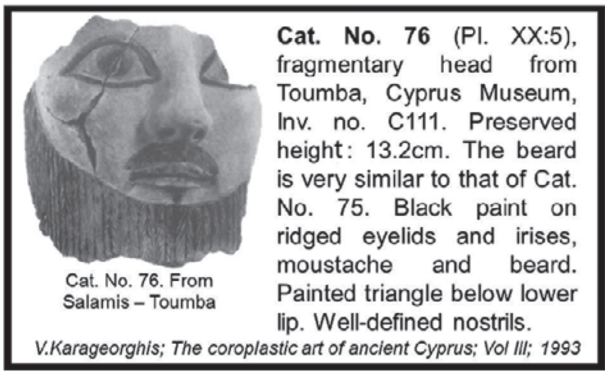

Figure 1. Archaeological description of a fragment (Karageorghis, 1993).

- Non-invasive chemical analysis

UV images

The surface of the objects was first studied with a UV light (a Blacklight set 15W, 46 cm, range UVA 300–400 nm, peak at 370 nm) and the images obtained with a Canon 1000D digital camera. The images were then analysed for the detection of restored areas, organic materials (fluorescent under UV such as madder lake or organic binders) and conservation state (possible presence of biological growth) (Figure 2).

Figure 2. Comparison of Salamis terracotta fragments analysed with naked eye and under UV light.

[3] http://www.gravitate-project.eu/

[4] Preliminary results on the decoration of the Salamis statues' fragments have been orally presented by the GRAVITATE scholars during the conference 'Salamis of Cyprus, History and Archaeology from the Earliest Times to the Late Antiquity, 21-23 May 2015, Nicosia.

Figure 3. High resolution image resulting from the digital microscopy analysis of a Salamis terracotta fragment.

Digital microscopy images

The clay morphology was studied by means of digital microscopy on fragmented edges of the objects. Microscopy observations (a Hirox KH-8700 digital microscope) is the first step of slip and pigment analysis which allows to detect traces of colour invisible with the naked eye, presence of colour mixtures or layer superimposition, particle morphology as well as fired/unfired type of decoration (Figure 3).

X-Ray Fluorescence spectra

Qualitative elemental analysis by X-Ray Fluorescence spectroscopy (XRF) was performed with an ARTAX-200 μ-XRF on coloured surfaces to identify general types of pigments. XRF measurements on fragmented edges of objects (bare clay) allow us to obtain quantitative characteristics of clay-concentrations of major (Si, Al), minor (Ti, Fe, Mn, K, Cr) and trace elements (Pb, Zn, Ba) (Figure 4). Qualitative and quantitative characteristics of clay elements (XRF) are combined with the microscopy data and used as markers for further matching/grouping of the fragments.

Fibre-Optics Reflectance Spectra and Colour Coordinates

Fibre-Optics Reflectance Spectra (FORS) (Figure 5) and colour coordinates (CIE-L*a*b*) of clay and coloured areas of the objects were obtained with a Ruby STIL

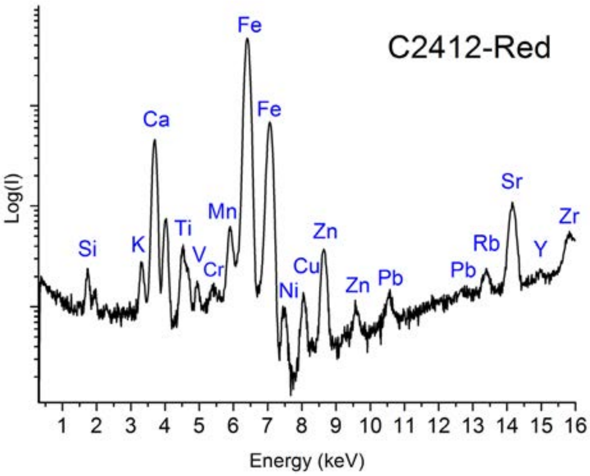

Figure 4. Example of XRF spectra of a Salamis terracotta fragment.

spectrocolourimeter. Depending on the specific pigment, the FORS data either supports or complements the data from XRF analysis for identification of general type of pigments.

- 3D digital documentation

The fragments were 3D documented in order to analyse them metrically and geometrically. According

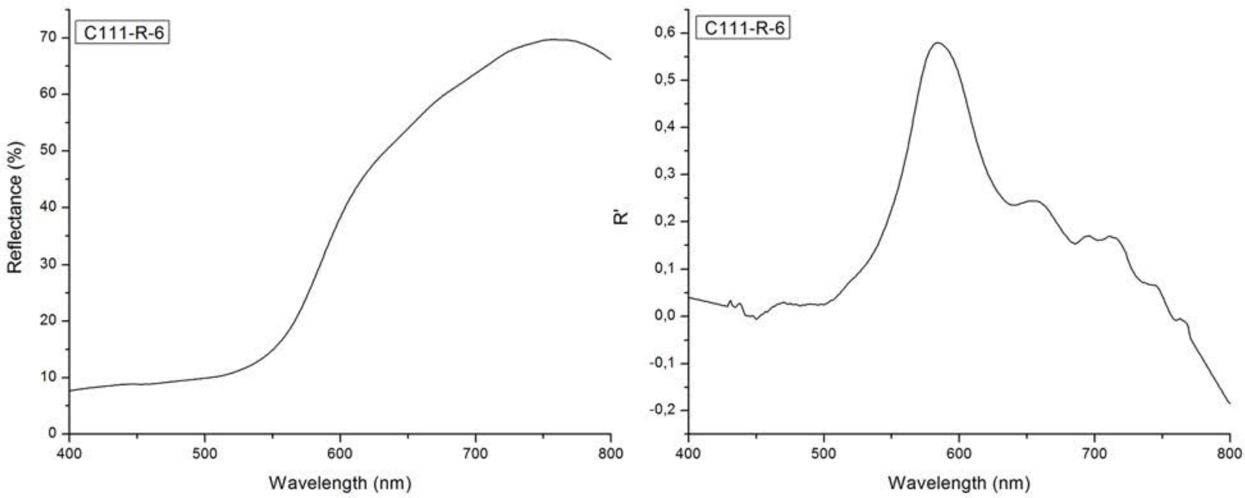

Figure 5. Example of the FORS and colourimetry spectra.

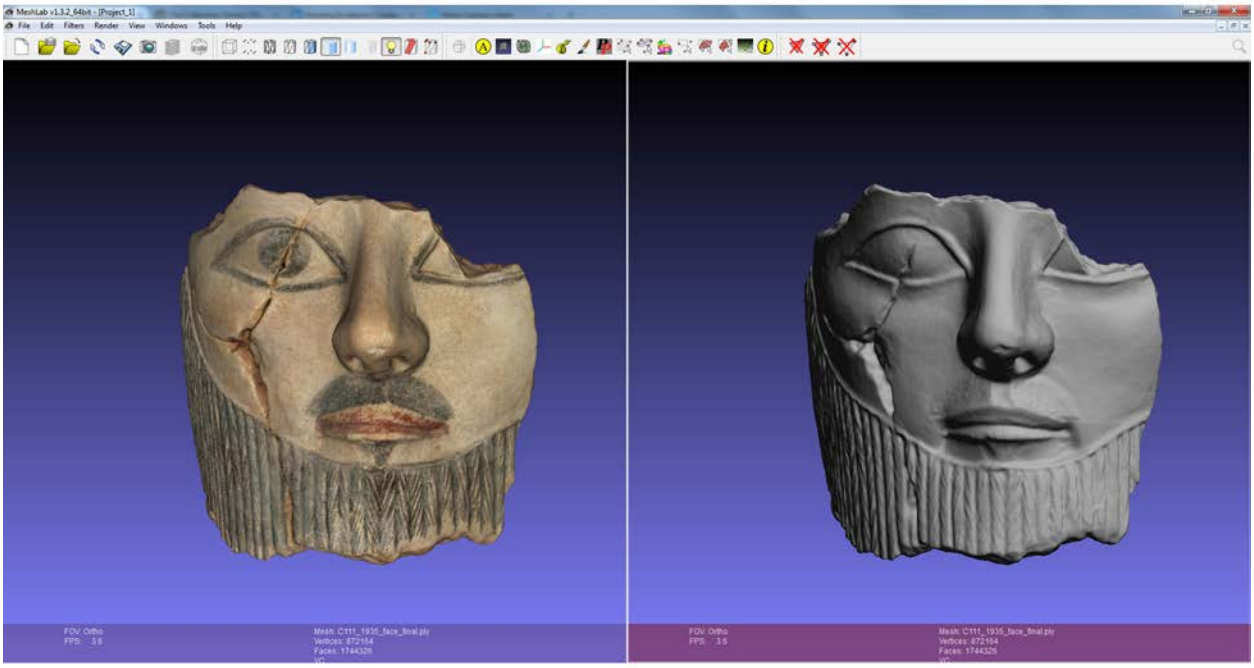

Figure 6. 3D model of a Salamis terracotta fragment.

to the size and the material of the items, the 3D data acquisition has been carried out with a NextEngine 3D Desktop laser scanner (Amico *et al.*, 2012). This specific laser scanner does not acquire a very high quality texture; therefore a photographic campaign of the same fragments with a NIKON D3X digital camera has been performed. The 3D scans of the fragments have been post-processed in Meshlab[5] for the realisation of the final models. The last step of the procedure consisted in the manual alignment of the pictures with the 3D models (Athanasiou *et al.*, 2013) (Figures 6 and 7).

After the realisation of the models, 3D comparison of similar pieces (heads, feet, legs and faces) has been performed.[6] Similar items were compared in CloudCompare,[7] calculating local distances between their point clouds. This is to identify the similarities and

[5] MeshLab is the open source software that allows us to post-process the meshes produced by the laser scanner and also to perform further analysis on the 3D models. The open source software is developed at the Visual Computing Lab of ISTI — CNR (Cignoni *et al.*, 2008). http://meshlab.sourceforge.net/

[6] The 3D comparison of the pieces and the 3D analysis are made for different aims within the GRAVITATE project activities: refitting of the statues, semantic study, similarity detection, etc.

[7] http://www.danielgm.net/cc/

Figure 7. 3D models' data set of the Salamis terracotta fragments from the Cyprus Museum.

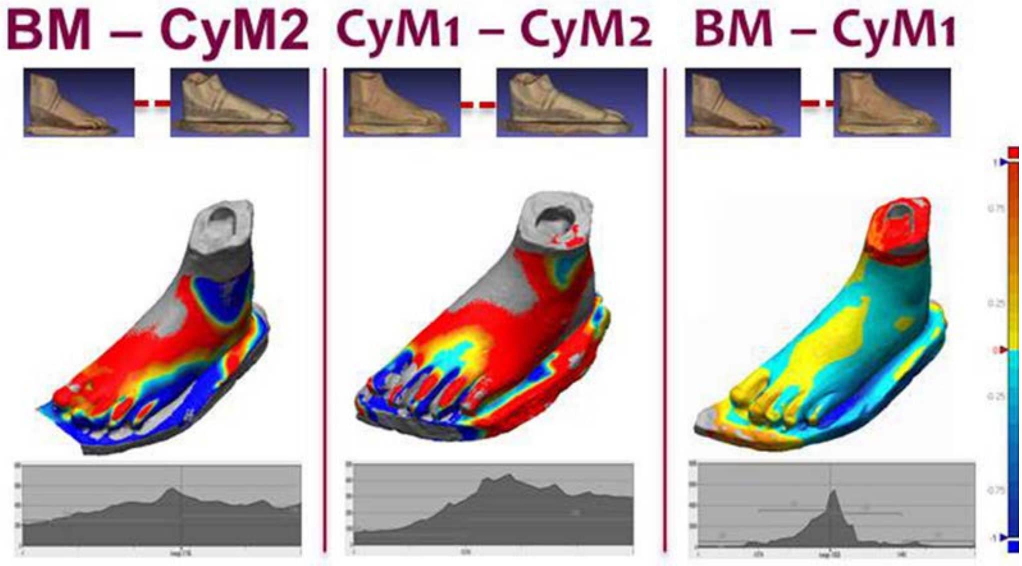

Figure 8. 3D models' data set of the Salamis terracotta fragments from the Cyprus Museum.

is therefore getting information about their production (e.g. use of the same mould?) or attribution to the same collection[8] (Vassallo, 2016) (Figure 8).

Towards a multidisciplinary ontological solution

Archaeology is a discipline characterised by different methods, techniques and theories. Organising data from multiple research domains is not a simple task. So far the most common solution was that one of the Digital Library paradigm, with the presence of publication of single findings. The possibility of integrating rich and structured information from all the heterogeneous sources can be the solution for solving the access to different and multidisciplinary data. A common and consistent representation of data enables us to filter related facts and information out efficiently from the mass of data, to be used by researchers. More specifically, Semantic Web technologies and formal ontologies can assure a common representation and management of this huge amount of different data. Our solution is to go towards a description through a common/global extensible schema represented by a formal ontology that guarantees '*integration without loss of meaning*' (Doërr, 2014).

An advanced solution is represented by the possibility to allow data publication in a semantic format, through mappings between archaeological resources and the CIDOC-CRM[9] ontology, in order to implement archaeological interoperability at conceptual level. The definition of mappings to CIDOC-CRM allows us to capture the semantic richness of our data and give the possibility of expressing the variety of information by the means of the classes and relations of the CIDOC-CRM and its extensions (Liuzzo *et al.*, 2014). Data integration through a CIDOC-CRM description will guarantee viewing information in a unified way (Felicetti, 2014). This would make explicit all the informative layers in order to be queried (and successively interpreted) as if they were accessible all at once.[10] There are different extensions of CIDOC-CRM available so far. For our aims we took into consideration the following ones:

CIDOC-CRMarchaeo[11] is an extension that supports the description of the archaeological excavation process and related activities. The model started from the idea that the excavation investigates features of the archaeological site in their stratigraphic context, considering also the events, natural phenomena and/ or human activities. It provides the tools to manage and integrate existing documentation. It also allows us to register technical aspects of the excavation and the observations made by the archaeologists during the whole process.

[8] Some fragments are not explicitly attributed to Salamis but associated for similarity. The comparison of the shapes can help us to figure out further information, e.g. a production with the same mould can lead towards the attribution to the same workshop and therefore higher reliability that the fragment belongs to the same group.

[9] http://www.cidoc-crm.org/Version/version-6.2.1

[10] The mapping to CIDOC CRM allows expression in RDF not only of elements and attributes but of entities and properties which relate the different values, allowing for an event based description which is much more precise and unambiguous, especially concerning the object itself (Hyvönen, 2012).

[11] http://new.cidoc-crm.org/crmarchaeo/ModelVersion/version-1. 4.1

CIDOC-CRMsci[12] is intended to integrate and facilitate the management, integration, mediation, interchange and access of metadata resulting from various scientific and analytical observations (e.g. biodiversity, geology, geography, archaeology, cultural heritage conservation). It can be an appropriate tool to register the scientific activity and its process (Doërr *et al*., 2014).

CIDOC-CRMdig[13] encodes metadata about the steps and methods of production ('provenance') of digitisation products and digital representations such as 2D and 3D data created by various technologies (all steps and parameters from data capture down to the end-user outcome). The digital provenance model has been developed mostly within the European project 3D–COFORM[14] (Doërr and Theodoridou, 2011; Tzompanaki *et al*., 2014).

The modelling data process

The archaeological data information of the Salamis terracotta fragments and its digital representation is structured and described according to an internal metadata schema. The metadata model has been developed for the description and publication online of archaeological items (artefacts, ancient buildings, archaeological excavations, etc.) and their digital representation, taking into account its digital provenance and the digital creation process (Ronzino *et al*., 2012).

The analytical data (physico-chemical analyses) produced within our case study are not described through any particular structure. The first step of the research consisted of revising the metadata standards used for scientific data. Subsequently we tested our internal metadata schema for implementation, in order to integrate in the structure the part related to the scientific observation, the process and the results. The solution offered by other metadata standards was not satisfactory for our scope and the development of a specific adjustment of the internal model for the scientific part was not accurate enough to describe our data. For this reason we decided to go towards a semantic/ontological structure, where the information and knowledge are represented as a set of concepts and relationships between those concepts.[15] On the basis of our data and of the available CIDOC-CRM extensions, a methodology for their integration and description has been developed.

The work consists of the following steps:

1. collecting a sample data along with their metadata structure
2. mapping the concepts of the sample to the entities of the CIDOC-CRM extensions that would be useful for describing our material
3. identification of missing concepts, adjustments or development of entities related to the specific extensions needed and used for the description of our case study
4. integration of all extensions in order to cover all concepts of our specific kind of data (integrating archaeological data, scientific data, analytical and digital ones).

The next step will be the implementation of a digital repository to integrate multidisciplinary data from our archaeological work.

According to our research, the objects are studied from different perspectives. A few practical examples of the procedure will follow.

a. Archaeological investigation

In order to explain the procedure followed for the description of the data concerning the archaeological part, we start with the object itself. In our case, a Salamis terracotta fragment is a material culture object, an archaeological artefact (E22_Man_made_object) that is part of an archaeological collection (E78_Collection). Archaeological collections can be described and mapped to CIDOC-CRM ontology, following both the core CIDOC-CRM and the CRMarchaeo. The collection of Salamis has the peculiarity to be divided in different parts, according to the different places where it is stored (the Cyprus Museum, the British Museum, the Fitzwilliam museum and other private collections). We can start from the identification of the place (excavation site) or the archaeological collection. As such, the Salamis archaeological site can be defined and described by the entity E53_Place, that in turn can be recalled back through the entity E9_Move, through *P27_moved from* and *P26_moved to* in order to describe the current position of the fragments and their various movements.

b. Analytical investigations

We describe here the part of the mapping related to the results of physico-chemical analyses as production of a scientific observation and the parameters of such analysis. The study is a sequence of events described within CRMsci: the scientific analysis (S4_Observation) is performed with a certain instrument (E22_ Man_made_object) set with specific parameters (E54_ Dimension). Revising CRMsci, it results that there is lack

12 http://www.cidoc-crm.org/crmsci/ModelVersion/version-1.2.3
13 http://www.ics.forth.gr/isl/index_main.php?l=e&c=656
14 More specifically, the model was developed in the context of three European projects: ACGT (on cancer research), CASPAR (on digital preservation) and 3D-COFORM (on production of 3D models for scientific and cultural use).
15 This can be achieved by providing access to such information through a semantic system relying on a domain ontology through accepted metadata and paradata (transparency of the information).

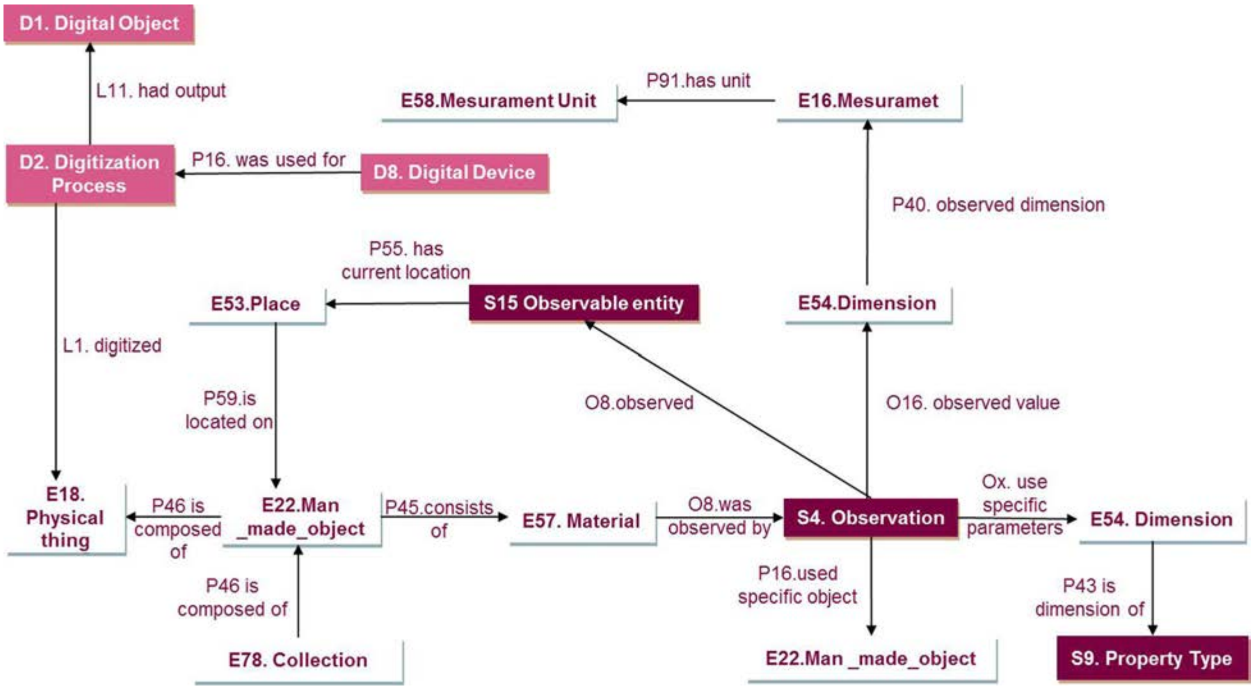

Figure 9. Mapping to CIDOC-CRM and the integration of its different extensions.

of a property for the specification of the instruments' settings. For this reason, we propose the introduction of a property "Ox_Use_Specific_Parameters", to be borrowed from the CRMdig extension (L13_used parameters) and adapted to the scientific description.[16] The scientific observation is performed on some points or features (S15_Observable entity) located on a specific place (E53_Place) on the object (E22_Man_made_object). The analysis (S4_Observation) provides measurements (E54_Dimension) that in case of physico-chemical analyses having a certain concentration (E16_Measurement) with own measurement units (E58_Measurement_Unit).

c. Digital investigations

All the steps of the digitisation process, from data acquisition to visualization, and the digital analysis, are described using CRMdig.[17] The integration of archaeological description and the digital description is done through the item (E22_Man_made_object) that is composed of (*P46_is_composed_of*) a certain material (E18_Physical_thing). E18_Physical_thing becomes a D1_Digital_Object through D2_Digitization_process, operated with a D8_Digital_Device.

[16] The study of the properties and other entities of the CRMsci is currently carried out by one of the authors of this contribution (G. Sorrentino) for her master thesis.

[17] The study of the CRMdig extension is part of the doctoral thesis of one of the author of this paper (V. Vassallo).

The final step consists of the integration of all the extensions in order to describe the concepts of our research and their publication online in a holistic way (Figure 9).

Conclusions

The paper details first attempts at creating a digital repository of typical archaeological multi-disciplinary research that aims at presenting primary data along with its interpretation process. Instrumental in this effort is the adoption of CIDOC-CRM and its extensions as the main ontology for describing the archived digital assets and as solution for semantic integration. Archaeological works inherently involve multiple techniques and resources, and the Semantic Web can serve as a good candidate for describing and interlinking the entities in a semantic and consistent way.

Open questions to be addressed in the future are: refinement of CRMsci and related metadata schema for the description of analytical measurements; a more detailed description of the decision-making process when acquiring data (paradata); the reasoning process implemented during the analysis of collected data through measurements and observations in order to get knowledge inferred from the axioms and assertions in the ontology and its individuals (Doërr *et al.*, 2011), linking to other archaeological data sets under CIDOC-CRM (and a possible publication at the Linked Open Data).

Acknowledgements

The authors would like to thank V. Karageorghis, V. Moutinho de Almeida, E. Athanasiou, and D. Abate for their collaboration. Moreover they would like to thank the Department of Antiquities of Cyprus for the possibility to access and study the Salamis terracotta fragments.

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Field and Laboratory Data Recording and Analysis

Mieko Matsumoto and Espen Uleberg (eds) 2018. ***CAA2016: Oceans of Data***
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
Oxford: Archaeopress

Integrated Methodologies for Knowledge and Valorisation of the Roman *Casinum* City

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Abstract

This contribution focuses on the ruins of the Roman town of *Casinum*, in southern Lazio, Italy, of whose past remains a significant archaeological area. The Archaeological Complex, despite the interest in its monuments, still lacks a structured survey that analyses the area as a whole, integrating individual events and emergencies with the context. The methodological approach of this work will develop and deepen the analysis and the knowledge of some monuments through an integrated survey of the site, with the aim of enhancing a complex landscape between an urban and archaeological context.

Keywords: *Casinum*, Roman urbanism, roman classical architecture, amphitheatre, Roman theatre

Introduction

The focus of this article is the documentation, interpretation, valorisation and communication of the Roman city of *Casinum*, which was a thriving city, particularly near the end of the republic and later in the imperial era (Carettoni, 1940).

This archaeological area, despite the interest and the importance of its monuments, has been studied from a primarily archaeological point of view. The area still lacks records that analyse the individual findings and the environment through a structured survey, in order to exploit the site in its entirety. From the ancient urban layout emerges the remains of the Via Latina, the Amphitheatre, the Theatre and the mausoleum attributed to the Roman matron Quadratilla, part of 'gens' Ummidia. Recently there have been some very interesting discoveries related to parts of a Roman villa dating to the imperial period, which should stimulate a deeper, organised method of study for the town planning system.

Our research includes several integrated methodologies and a large staff. The main part involves a laser scanner survey of the whole area. There are many others steps involved, including digital processing of documentation, interpretation and communication of the Casinum Archaeological Area. Another objective of our work is to integrate the analytical data from the laser scanner survey of a complex monument with a more traditional and direct analysis performed through watercolour drawings in order to document the intangible aesthetics of the site (Cigola *et al.*, 2016).

The research group is formed by DART; Laboratory of Documentation, Analysis, Survey of Architecture and Territory of University of Cassino; by CRITEVAT; Centre in Riety for Engineering Research for the protection and enhancement of environment and territory; Sapienza University of Rome, and by LAREA; Laboratory of Survey and Architecture, Engineering Area University of Rome 'Tor Vergata'. The Cassino National Archaeological Museum 'G. Carettoni' and the 'Archaeological Park of Casinum' are also involved and collaborate in the research.

Cassino and Montecassino Abbey

Today, Cassino is a modern town between Rome and Naples. The city has been completely rebuilt after the destruction during the World War II, and it is quite famous for the Montecassino Abbey. Cassino is located just below the mountain where the Montecassino Abbey is situated. The history of the city of Cassino and the Benedictine monastery of Montecassino are very closely linked. The cities built environment appears to be historically characterised and consolidated up to the Second World War, when any traces of its past were lost.

The history of Cassino is still of importance, and dates back to ancient times. The first settlement of the site dates back to the sixth century BC, when first the Volsci and then the Samnites permanently established themselves in the Liri valley, building the first houses of *Casinum* (the ancient city). The Samnite centre was then occupied around 272 BC by the Romans who made it a *castrum* (fortified place) with a settlement of about 4,000 veterans. From Roman prefecture, *Casinum* became *municipium* and in the third century AD it was

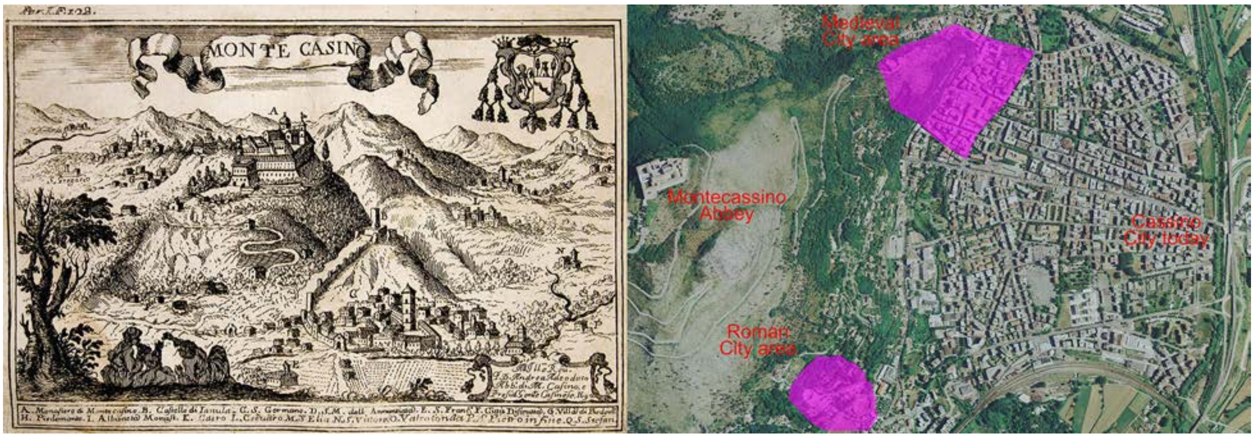

Figure 1. Left: 'Monte Casino' in G.B. Pacichelli, Il regno di Napoli in prospettiva, Napoli, 1703, general view territorial area; right: current general plan, the Roman and Medieval city area with Cassino city today, in the Southern part of Lazio region.

Figure 2. The town of Cassino before and after the Second World War.

granted the right to citizenship. The city reached its peak towards the end of the republic and during the imperial period, and then gradually lost its relevance. In 529, with the settlement of St. Benedict (founder of Montecassino Abbey and Benedectine monastic order) among the ruins of the pre-Roman and Roman fortified acropolis, the city's history became inextricably linked to that of the Abbey. The territory around the Abbey was named 'Terrae Sancti Benedicti' (the Land of St. Benedict), and was under the rule of Montecassino Abbey.

The Abbey occupied a central and dominant location within this large territory (Figure 1), and it exercised direct control over the various urban centres and their appurtenances and the ancient Via Latina connecting the north and the south of Italy (Cigola, 2005).

The Roman site was slowly abandoned in favour of a new urban centre further north. The city re-founded by Bertario (856–883) was called *Eulogimenopolis*, the 'City of St. Benedict'. Later, the city under the name of 'San Germano', was fortified and became the administrative centre of the 'Terra di San Benedetto' (Land of St. Benedict) under the jurisdiction of the Abbey of Montecassino. The medieval town of San Germano, later called Cassino, surrounded by walls which from the Rock (Rocca Janula), spanned the entire urban core and would retain this shape substantially unchanged until the Unification of Italy.

The Unification determined a substantial break between the old site of *Casinum* and the new urban core. However, the ruins, adjacent to the road to Rome, were crossed by one of the roads leading to the abbey, and one of the most representative monuments of the Roman city, the so-called tomb of Ummidia, was transformed into the church 'of the Crucifix'. The well-known events of the last world war completely razing to the ground the entire area, which was the hub of the German Gustav defensive line. This created the foundations for a new reconstruction, which saw, especially in the 1950s, a period of extensive urbanisation affecting, sometimes quite invasively, much of the archaeological area and giving rise to a complex territorial reality between new and old (Figure 2).

The Roman city

The city of *Casinum*, after becoming a Roman town around the first century BC, began a process of consolidation of its urban structure that necessarily took into account the particular topography of the places and the existing conditions, as well as a circuit of pre-Roman walls. A first and important urbanistic transformation took place in the Republican period and had as main axis via Latina Nova, which directly connected *Casinum* and *Aquinum* towards the city of Rome (Ghini and Valenti, 1995; Coarelli, 2007).

Archaeologist Paolo Sommella in his work succinctly describes the urban layout of the Roman town of Cassino like this: '... in the few buildings still visible that, arranging themselves in southern, flatter part of the urban area, delineate a regular plan. Both the theatre and the amphitheatre, outside the city and coordinated with the road layout, meet the criterion of orography exploitation and can be classified chronologically in the early stage of the colony, with restorations in the first imperial age' (Sommella, 1988).

The organisation of the city was divided mainly on three terraces lying on the hilly orography of the site, of which a large part of the original substructures still exist, expanding the city to the east, outside the city walls, in the steepest area (Figure 3). The settlements during the Augustan period, the late imperial period when the city (at the end of the 1st century BC) reached an area of about 10 hectares, led to hypothesise an urban network structured in the shape of a square of two *actus.*

This pattern is still detectable today with metrological swings in insular forms, which may result from adjustments to local building requirements (Tanzilli, 2007).

Important citizens contributed to the monumental interventions and architectural manifestations of *Casinum*, including Gaius Ummidius Durmius Quadratus (12 BC–60 AD) politician and soldier, Governor of Syria, and especially his daughter Ummidia Quadratilla (27–28 AD–107 AD). Ummidia was an important figure in her time, and was mentioned by Pliny the Younger in his Epistulae (Epist. VII, 24).

The monumental structure of the present archaeological area preserves traces of the period described in some major findings that were the subject of the first survey for this research project (Figure 4). The theatre, the core of the Augustan town plan, brought to light in the years 1935–1936, damaged by bombing in 1944, and the subject of restoration around the 1950s and again in 2001, has a semi-circular auditorium partially leaning on the natural slope of the hill and, at the back of the scenery masonry, there are traces of two porches. The amphitheatre, dated to the second half of the first century AD, has an elliptical shape of small dimensions. Created in the near suburbs of the city, it is only partly built above ground, using the slope of the site to limit the construction work for the terraces. The location, although outside the city, has the transverse axis aligned to the grid of the Augustan plan. Among its various representations, some drawings of Francesco di Giorgio Martini are preserved, who in 1494–1495 travelled to Cassino and included the amphitheatre among his sketches, accompanied by some notes in the margins which clarify functions and constructional and typological characteristics (Tanzilli, 2004).

The so-called tomb of Ummidia (1st century BC–1st century AD), is a Greek cross building, with the central part covered by a hemispherical dome intersected by four arms. At the end of the eleventh century, the structure was converted into a church then abandoned, later restored and dedicated to the Crucifix, and subsequently giving the name (Crocifisso) to the archaeological area (Giovannoni, 1972).

After the bombing of the Second World War, the restoration almost completely eliminated the latter stages of the church (the medieval and late 17th century phases of the church) returning the building to its original Roman connotation. The structure, in part basement, is made entirely of large dry limestone blocks finished on the inside but rough on the outside, that has a brick structure finishing. The tomb, for its singularity in the stonework, is of particular interest in its constructive geometric aspect, and deserves adequate depth of analysis from the data collected (Maiuri, 1938).

The Nymphaeum, called Ponari, also dates to the 1st century AD and has a rectangular plan with a barrel-shaped roof, closed on three sides and fully open on the front. The building is connected to the well-structured floor plan of a rich *domus,* which presents valuable floor mosaics, as well as fragments of the walls of the rooms preserved for more than 2 m in height. The wall decorations are articulated in architectural schemes with small paintings of mythological-symbolic subjects or idyllic-naturalistic themes (Figure 5) (Valenti, 1992).

Digital survey and representation models of the archaeological site

The use of surveying techniques and digital representation for the analysis and documentation

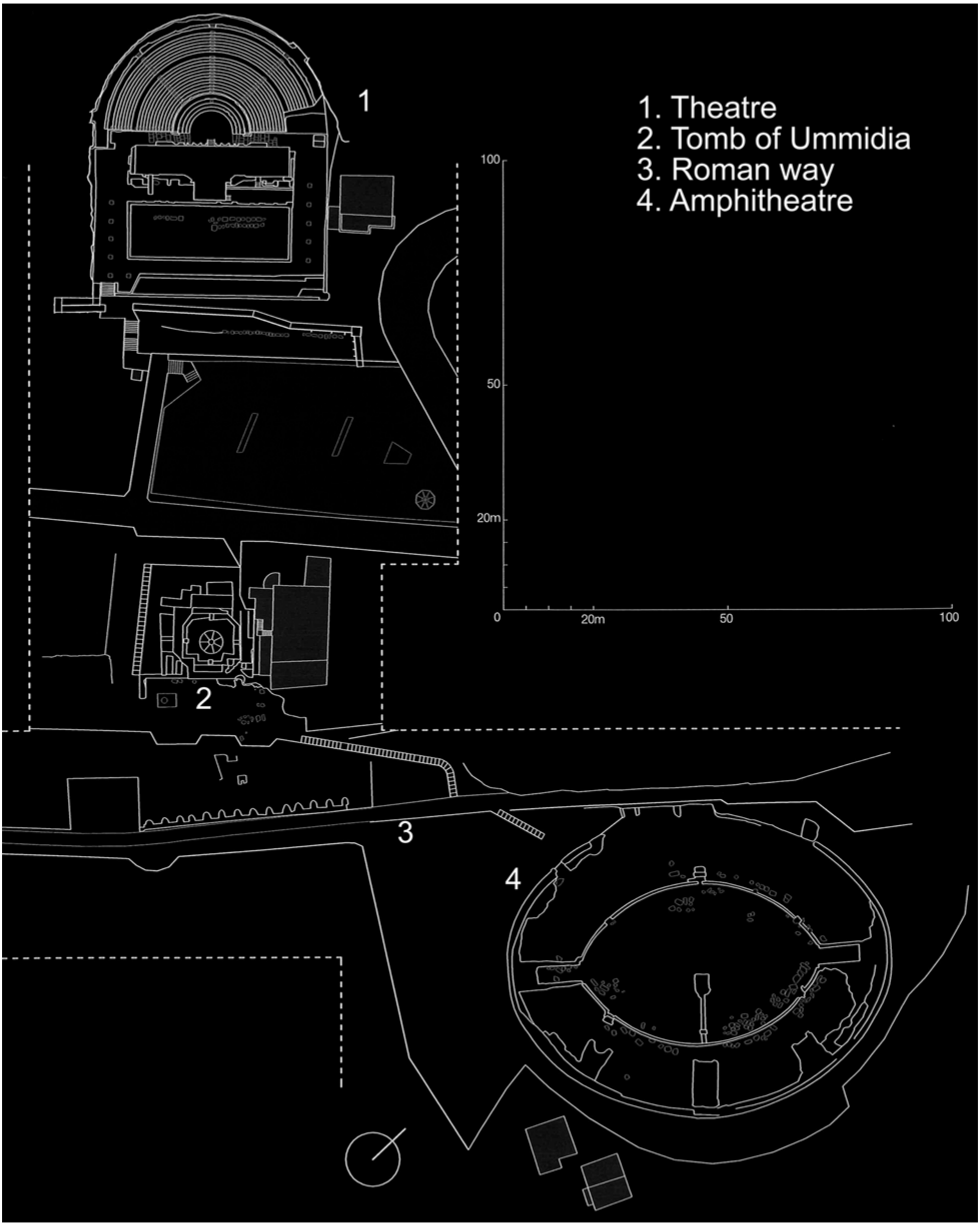

Figure 3. Architectural plan of Casinum Roman city (partial area) with the Theatre, Tomb of Ummidia, Roman way and Amphitheatre.

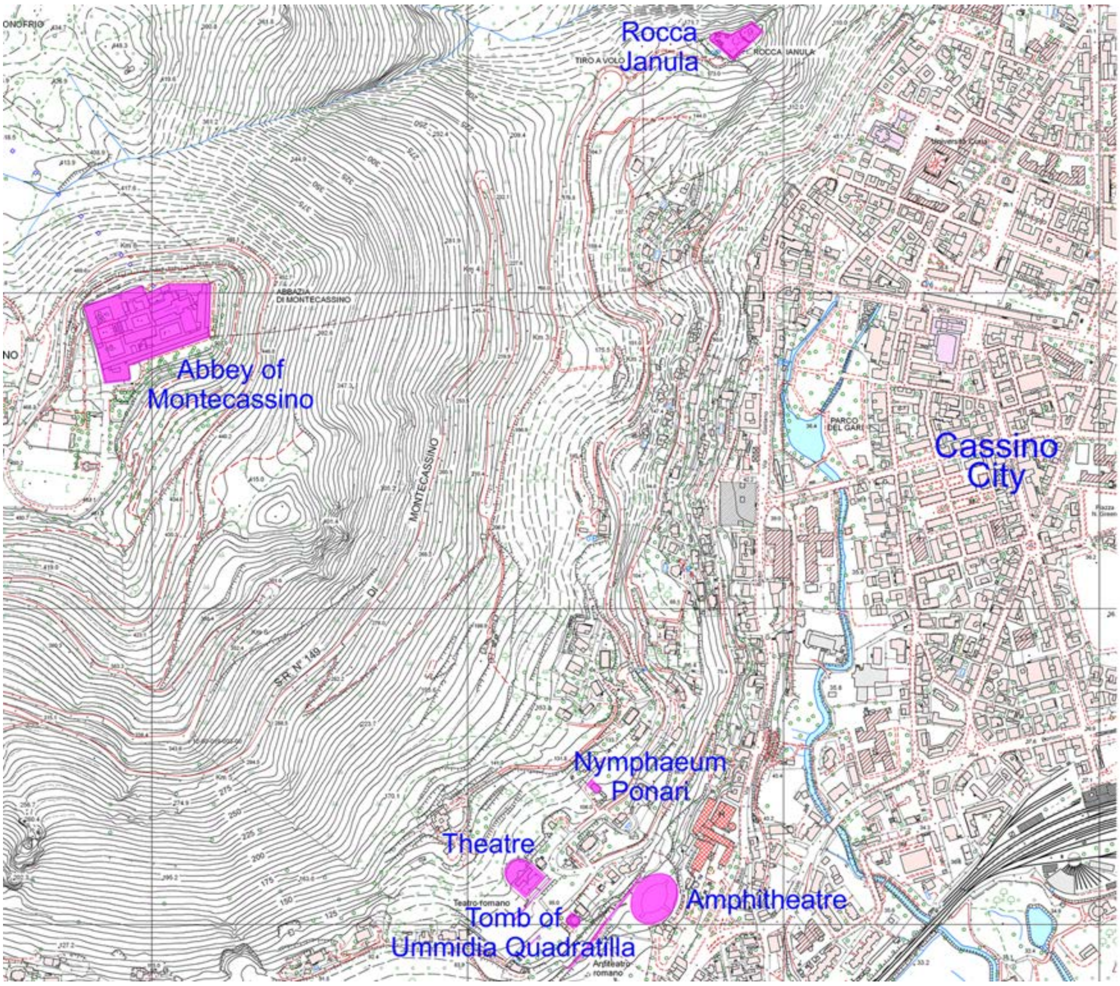

Figure 4. General plan view: Casinum Roman area, Abbey of Montecassino, Rocca Janula and Cassino city.

of archaeological sites today represents a valid and innovative support to protect and valorise the numerous archaeological sites, large and small, that dot our territory. Moreover, some of these sites are known to archaeologists and superintendents, but often barely visible or even unknown to the community because they lie outside of the local tourist circuits (Paris, 2015a).

In many fields of architecture, archaeology and landscape, digital technology has enormous potential. In recent years there has been a widespread use of these techniques with the consolidation of new methodologies in survey and representation. Digital technology, on one hand, makes certain activities related to survey easier, but on the other hand, produces strong specializations within archaeology, with resulting representations or products that sometimes do not talk to each other because they are based on different platforms and standards.

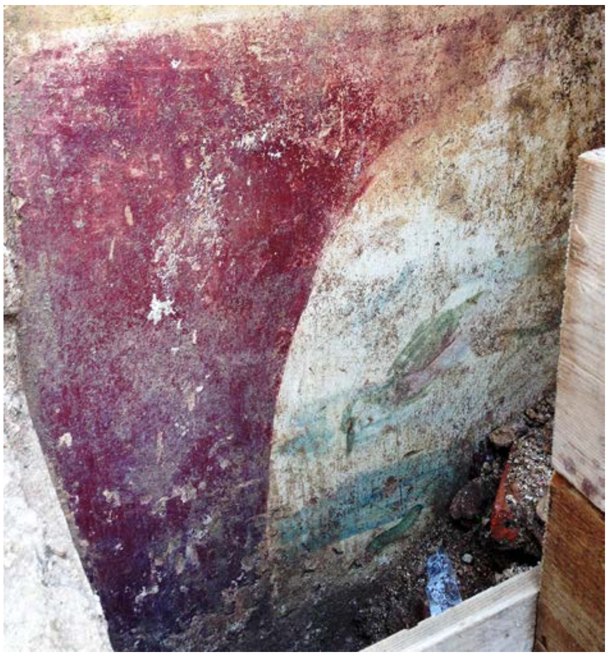

Figure 5. Nimphaeum Ponari: remains of walls with frescoes of high aesthetic quality.

A goal of the research activities on the archaeological site in Cassino was to prepare a digital box containing historical and archival information, the digital metric data acquired now and in the past, and the several products produced from qualitative and quantitative standards shared by the scientific world.

Before considering the merits of the integrated digital survey specificity applied to archaeology, it is appropriate to recall briefly some concepts that form the basis of the architectural survey, which are today widely adopted by scholars of this discipline. Digital technology has produced, in recent years, a convergence and integration of different instrumental survey methodologies; some already known, such as topography (merged into the wider scientific area called geomatics), more innovative methods such as a laser scanner, and others that are quickly converted to digital forms, such as photogrammetry (Paris, 2015b).

In the field of *3D shape acquisition*, the integrated digital survey it configures is the interaction and integration of three distinct methodologies: topographic, laser scanning, photogrammetric. In the archaeological survey the combined use of these three techniques is very common today, since each has distinct characteristics for costs, mode of acquisition, processing and data management (Ballabeni *et al*., 2015).

The experiences in progress in Cassino are significant for the particularities of the site; highly integrated with the existing urban fabric and with an orography that makes the stratigraphic study of the different archaeological phases more challenging. What is visible today is only part of the Roman *castrum* and in some areas, such as that of the Nymphaeum Ponari, they appear as isolated incidents, although it is generally agreed that these should be seen and relocated within a unitary urban configuration. Within this *unicum* there are archaeological remains of different types, sizes, conditions and construction features, therefore it is important to adopt strategies for acquiring and processing data which are related to the specificity of individual archaeological features. The starting point for digital data is a point cloud, whether using a laser scanner or photogrammetry. The point cloud is a set of discrete points, more or less dense, each marked by positional values (coordinates X, Y, Z) and other values that depend on the characteristic of the material (as for example the value of the reflectance using the laser or the RGB colour value with photogrammetry) (Figure 6).

The main characteristic of a point cloud is its resolution, that is, the amount of points in the unit volume. In the archaeological survey, this value is particularly important because there is the need to document not so much the simplified geometric model, but the minute feature details of the materials that make up the archaeological remains (masonry textures, stratigraphic sections, state of conservation of the materials, etc.). It is therefore necessary to first of all design the acquisition campaigns with the aim of processing a point cloud with a high resolution. This means working with large files (often difficult to handle without powerful computers) and using specific software. There is also the need for the development of models from point clouds that are easily used by unskilled operators.

Figure 6. Theatre: 3D point cloud used for processing.

An important phase of processing on the archaeological site in Cassino has been to define appropriate representation models. The documentation of the territorial level, and up to the detail of the whole complex, including occasionally adding the information that is gradually being drawn together in collaboration with archaeologists and historians, requires foresight for the representation model chosen. The acquisition activities made to date have been: the global topographic network points, laser scanning and photos taken with APR systems (drones) (Figure 7). The archaeological area is substantial, and goes from the theatre in the North to the amphitheatre to the South, and includes the tomb of Ummidia Quadratilla, the Via Latina and other minor ruins; the archaeological remains visible and recognised today are an important part of the whole area of the ancient Forum (Figure 8). More detached is the Nymphaeum Ponari. It is already largely excavated, and further excavations have unearthed walls with beautiful frescoes.

In some cases a method of acquisition was adopted that integrated scanner-laser and photogrammetry; above all when there was the real possibility to perform flights using drones and the need to perform accurate observations from terrestrial fixed stations. In other cases, such as on the Nymphaeum Ponari, only laser

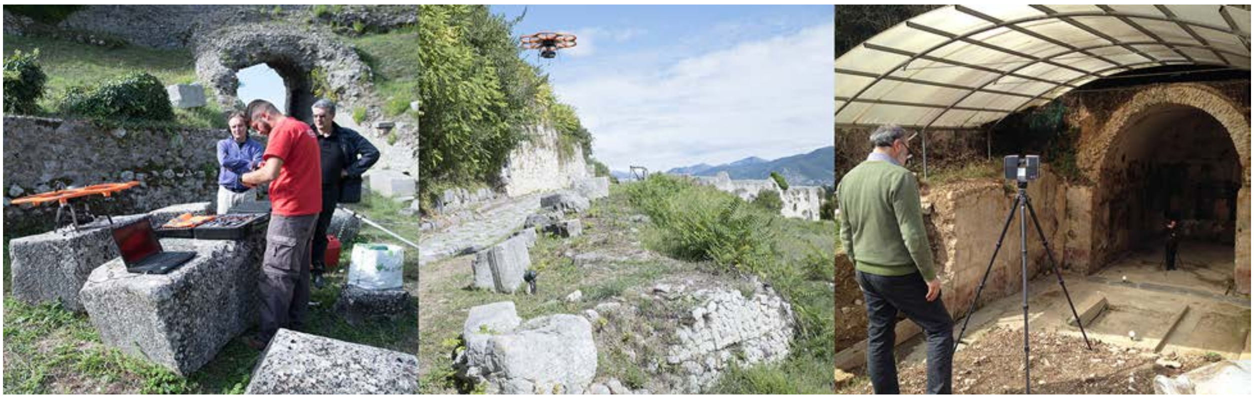

Figure 7. Archaeological area: acquisition activities with APR systems and laser scanning.

Figure 8. Archaeological area: objective-geometric model.

scans were used since there were no conditions suitable for flights with the drone. Particularly accurate was the acquisition of the Tomb of Ummidia Quadratilla which, though geometrically simple inside, outside presents a particularly fragmented articulation, which makes it necessary to document in detail in order to fully understand the complex layering in the various historical stages of reuse of this exceptional monument.

For the scanner acquisition, a Faro Focus3D 130X was used, supplied by CRITEVAT. For aerial photo acquisition, two drones were separately used. The first drone (APR — Aircraft Pilot in Remote) is Aibotix X6

Figure 9. Architectural cross section with the 3D point cloud overlaid.

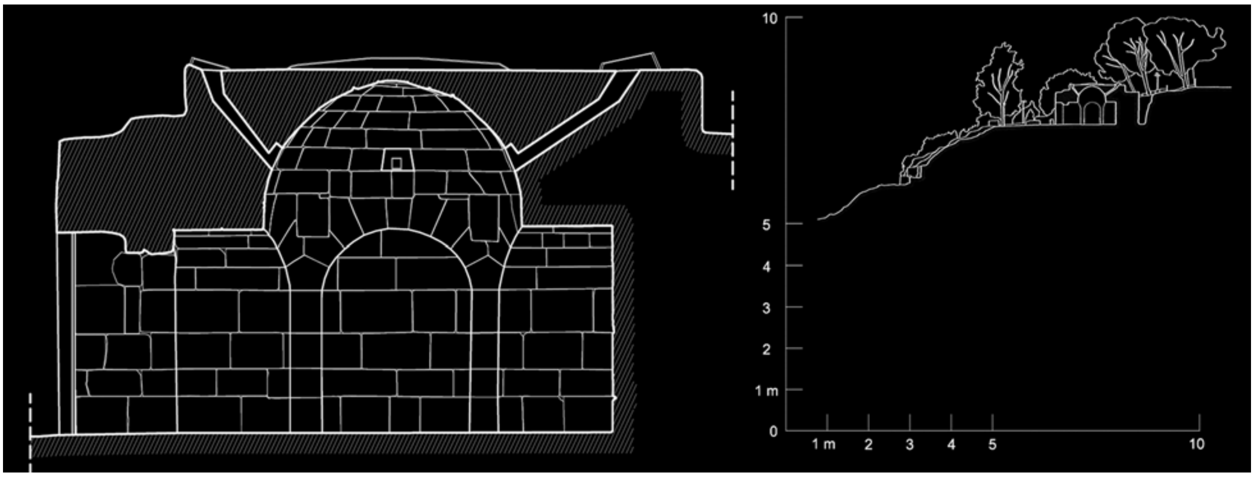

Figure 10. Tomb of Ummidia: architectural cross section.

V2, a hexacopter equipped with, among other things, a GPS receiver, accelerometer and ultrasonic sensors, and digital camera Olympus E-PL5 to 17.2 megapixels. A second drone was also used, a DJI Phantom 3, which is a quadcopter equipped with GPS receiver, accelerometer and barometer, with an integrated digital camera, which recorded videos at 1080p, FullHD. In total 8 flights were made, 4 with the first drone and 4 with the second. The flights concerned the following areas: the interior of the amphitheatre with 412 images (two flights), the indoor Roman road to the main archaeological site with 112 images, the Tomb of Ummidia with 180 images, and the theatre and its context with four different flights during which Full HD video at 23 fps, 1920×1080 frame, were registered (Apollonio *et al.*, 2012).

As for the processing phase of the models, plans and sections were obtained to different scales, from the general which includes the whole excavated area (Figure 9), to those of the detail which concern in particular the Tomb of Ummidia and the Nymphaeum Ponari. For the tomb a detailed survey was made of the large stone blocks that make up the single chamber

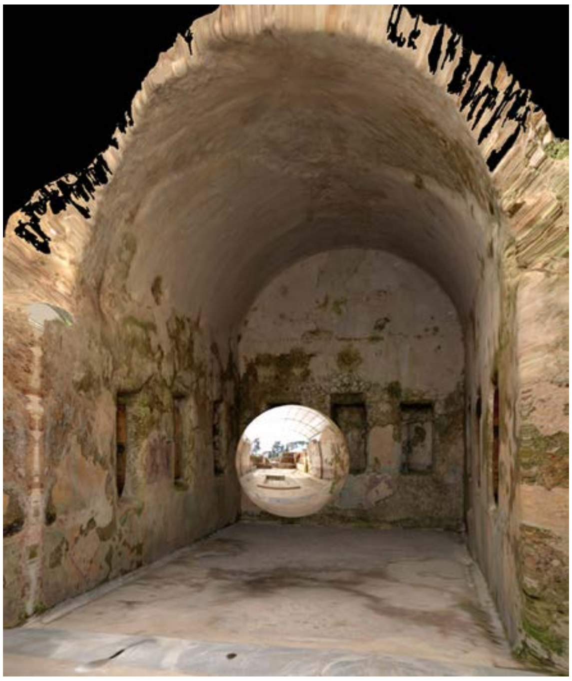

Figure 11. Nymphaeum Ponari: 3D model with spherical panoramas.

with Greek cross plan. This studied in particular the shape of the ashlar connecting the vertical walls and the whole system of the vaults, formed by a dome connected to four barrel vaults, with the intersection curve not planar but a hump (with all the problems of stone cutting) (Figure 10). On the dome there are four diagonal holes, presumably needed to illuminate and ventilate the tomb. Also interesting is the trace on the stone flooring that most likely represents the projection line of the dome on the floor.

On Nympheum Ponari, the laser scanner survey was integrated with spherical panoramas made with an external camera on a panoramic head. This made it possible to replace the image of the internal camera with a higher resolution one in the 3D model (Figure 11).

The photos made with the external camera have enabled the use of the HDR technique to achieve exposure compensation. On the walls of the Nympheum there are many small traces of the different stratigraphy. These traces can help the archaeologists to understand the multiple coatings that have taken place over time. A careful study of these traces is possible only through the right integration of the metric data from the point cloud and the high resolution photos. The survey of the Nympheum Ponari also takes into account the current/recent excavations that brought to light the remains of walls with frescoes, which are very well-preserved and of high aesthetic quality (Ippolito and Cigola, 2017).

Documenting the colours of archaeology

To comprehensively document the identity of a space, this part of the study focused on merging suitable chromatic representations with the data and analytical information obtained from the survey and acquisition operations carried out using technological instruments. We performed a meticulous, direct interpretation of the archaeological site to locate not only the remains and systems still visible in the area, but also all the seemingly invisible traits, enabling its univocal

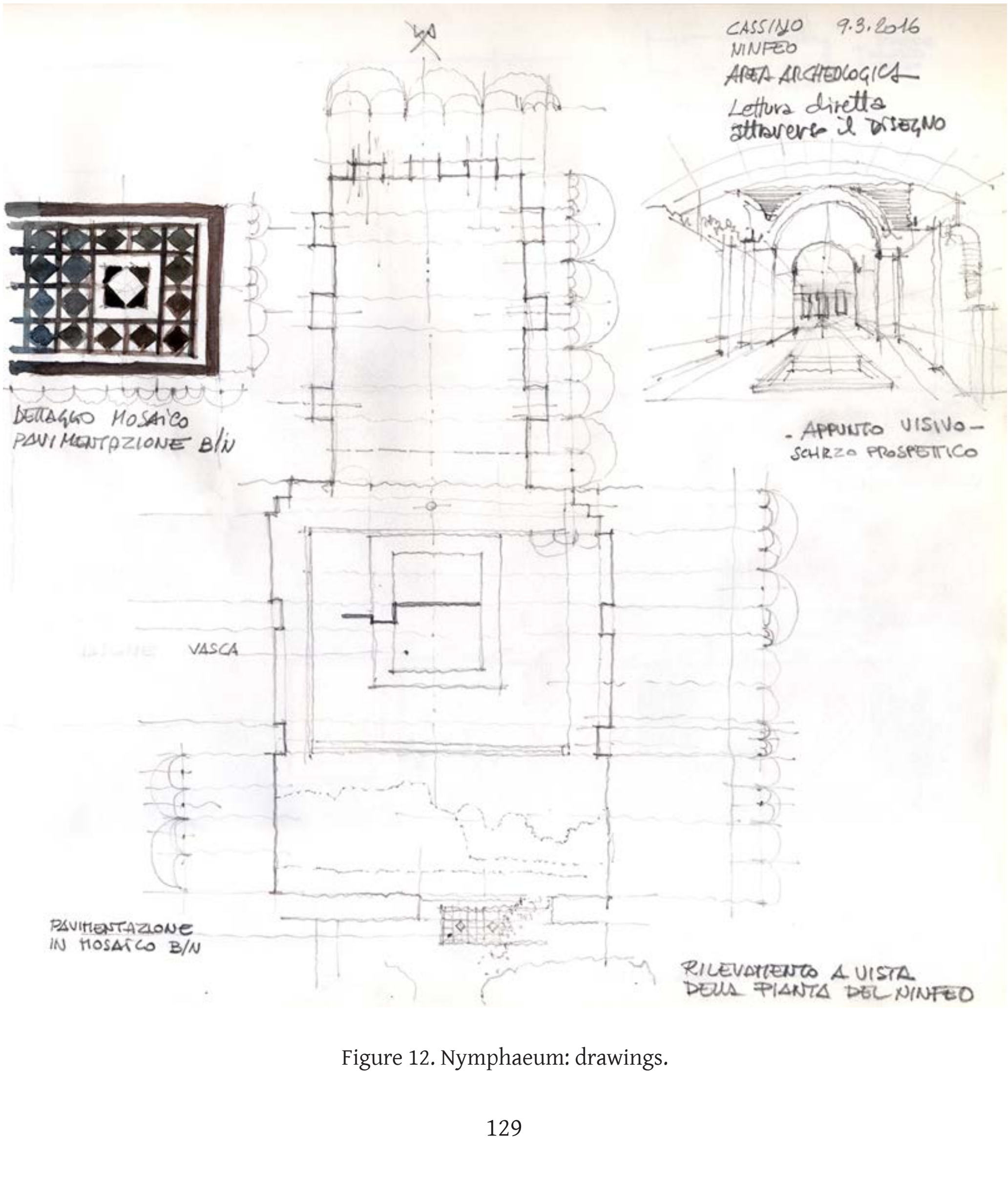

Figure 12. Nymphaeum: drawings.

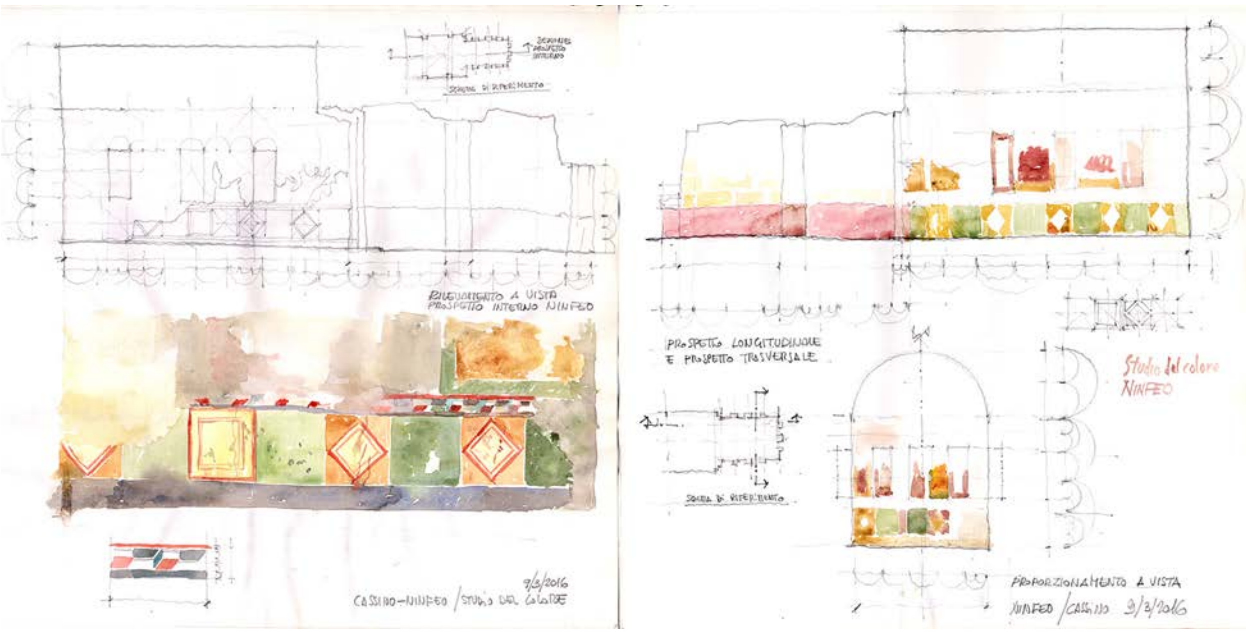

Figure 13. Nymphaeum: drawings.

recognition and identification, for example the balance and disharmony of forms, atmosphere and colour.

The route we chose more or less coincides with the tourist itinerary inside the archaeological area. All the more important buildings are located along this route; they include the tomb, amphitheatre, theatre, nymphaeum and the old roads not only running between the buildings, but also between the buildings and the neighbouring green area. The multiple observation points we chose along this route were the ones we thought were best suited to the task; we drew each architectural object, trying to emphasise its typological characteristics and the chromatic quality created by its exposition to natural light while it was being represented (Chiavoni, 2010).

After carefully examining the site we then elaborated it conceptually: a sort of subjective inspiration, like an artist who takes notes before starting to work, or makes visual studies and drafts preparatory sketches and tests to trigger the multiple interpretations they need to decipher its complexity.

These drawings sketched in situ quickly become a personal collection of notes, critical graphic ideas, sometimes intimate and rapidly sketched, but always packed with content. The album or notebook containing the drawings becomes a bona fide collection of memories and ideas reflecting the draughtsperson's ongoing search for perfect forms. Sheets of paper filled with sketches, graphic notes and all kinds of drawings in order to truly understand every display of the noble power of nature; an attempt to capture the beauty of the landscape, sky, vegetation and the endless variety of natural details. It involves studying the history of an archaeological site and proposing the important tradition of this graphic, real-life exercise: clues; sketches of ideas, formulas, diagrams, patterns, notes. All these preliminary scientific studies convey a desire to recapture a slow exercise: real life drawing. An exercise requiring great ability and concentration, and one which, unlike other methodologies, prompts reflection is still a crucial element behind the acquisition of knowledge.

To establish the volume and geometry of what could still be seen of the Nymphaeum we made numerous visually proportioned, general and detailed pencil and colour drawings (Figure 12). Instead we executed detailed watercolours of the intact parts of the decorations on the interior walls (Figure 13).

Our disciplinary sector is positively reassessing watercolours because they make it possible to accurately record the colour nuances of materials, transparencies and patinas; even the randomness of strokes by an expert can sometimes enrich the graphic composition. To portray the elegant form and strict geometry of the amphitheatre we used perspective sketches and bird's-eye views (Figure 14). Chromatism is the expressive use of colour thanks to the various washes, used to depict the vegetation now sprawling across most of the amphitheatre. The colour green not only represents empty space and acts as a backdrop for the ruins still present in the site, it also forcefully evokes

Figure 14. Amphitheatre: watercolour drawings.

the role of the amphitheatre and helps to dynamically characterise the central space of the arena (Figure 15).

In some ways, choosing one technique over another influences the graphic process and allows the draughtsperson to use several styles; harsh or soft, approximate or detailed, pictorial or graphic, as the case may be. Characterisation of the drawings of the amphitheatre was achieved using strong colours, especially to portray the natural surroundings, influenced by the day and time when the drawings were made. This chromatic contrast helps to underscore the current state of the walls or individual stones still standing along the circular perimeter or inside the arena itself.

Any graphic technique can be used to convey the image of an archaeological site, but using colour imbues it with a much richer emotional charge. In fact, since a drawing often has to represent incomplete elements (e.g. part of a wall or a painting or fresco) the naturalistic image has to be mediated and obviously adapted to the size of the drawing. Indeed, the choice of colour technique is extremely important if the draughtsperson intends to produce a clear, comprehensible drawing. The study of the archaeological site in Cassino is a personal narrative with a precise itinerary executed to record the undeniable immaterial, intangible heritage that makes every site unique and recognisable. History is expressed in the drawing in order to find, amongst the ruins, the thin red line of a logic that can interpret their original form. By studying in-depth the incomplete forms reminiscent of its primary, generating forms and load-bearing structures, one realises that these fragments represent an important part of the memories of the past, and that the artefact and all its most significant details have to be carefully documented and checked. This methodological process has always been considered, and is still considered, a key moment in the training of all architects, archaeologists and intellectuals in general because it allows the person in question to establish not only a dialogue with history, but also a dialogue between different fields of knowledge and learning.

In the eighteenth century travelling in Italy as part of the Grand Tour became very popular in Europe; people came to study ancient artefacts, monuments

Figure 15. Amphitheatre: watercolour drawings.

and landscapes, portraying them in sketches and watercolours. Likewise, today we feel the need to use drawings to study our cultural heritage. The Grand Tour, dedicated to improving one's knowledge and skills, involved starting and ending one's journey in the same city; the Tour lasted anything from a few months to several years, but the final destination was always Italy due to its immense, incredible cultural heritage. At the time archaeologists and architects were relentless travellers who wanted to 'capture' the ruins and places they visited; they made sketches, drawings and, often, watercolours. The beautiful exhibition held in 2010 in Rome and entitled 'The Colours of Archaeology' bears witness to their efforts: during the exhibition 100 drawings and watercolours were displayed to narrate the history of the production of documents concerning archaeological finds in Rome between 1703 and 1948 (Filippi and Attilia, 2009).

The exhibition was curated by the Historical Archive of the Special Superintendency for the Archaeological Assets of Rome; scientific collaboration was provided by the State Archive of Rome, the Deutsches Archäologisches Institut in Rome and the Superintendency for the Archaeological Assets in Lazio. The exhibited material revealed one important aspect: that images of the discovery of the archaeological site were crucial not only to understand the ancient ruins, but also later, when the data was being processed: drawings made it possible to mentally recreate the site and hence understand the ancient artefact. The exhibition repeatedly proved that these drawn images or watercolours were the only remaining images bearing witness to a lost archaeological heritage. It highlighted issues extrapolated from archival documents about the history of Roman archaeology and also tackled another topic: the birth of a specific scientific culture and its protagonists — the surveyors, architects, engineers and painters who worked side by side with the archaeologists. Synergy between experts from several disciplinary fields always makes it possible to perform further, in-depth studies of all the surveyed data: not only to acquire greater knowledge about a place, but also to draft interventions regarding the maintenance, reuse or requalification of any archaeological site (Chiavoni, 2012).

We believe the time has come to include these significant chromatic representations in any analysis, documentation and communication of archaeological and architectural cultural heritage. Our objective should be not only to increase the data provided by survey and achieve a more complete and comprehensive monitoring even of the intangible aspects that are difficult to measure and record, but also to build up a folder of valid and complete data. An interactive cataloguing system, including the survey drawings and watercolour images of the archaeological site in Cassino, can become a continually updatable database, one which is valid for operators in this field as well as for those involved in the maintenance and enhancement of this area.

Conclusions

The use of digital detection and representation techniques for the documentation and study of archaeological sites and historic buildings, has increased significantly in recent years. After an initial test phase, a practice that is common among Superintendencies, a team of surveyors, archaeologists and scholars has been established, according to which digital technology can be an important means for optimising resources for the conservation and enhancement of the cultural heritage that are so widespread in our territory. From this point of view, the research, which is still in the preliminary phase, aims to analyse, produce knowledge and increase appreciation of Roman *Casinum* in its entirety and in detail, and for its findings to be contextualised in a complex landscape between the urban and archaeological area.

Casinum Archaeological Heritage includes tangible and intangible goods. Keeping this site in the present for the future is connected with actions such as Identification, Analysis, Preservation, and Restoration, with specific technical meaning. Each of these areas of intervention includes not only technical actions and expertise, but requires more cultural evaluations in respect of the concept of Archaeological Heritage. In summary, Casinum Archaelogical Area can be also understood as a complexity of activities through a very wide range of disciplines whose aim is to identify, evaluate, and preserve past achievements for the benefit of subsequent generations by preserving the memory of the past and inspiration from it for future enhancements and appreciation of current results.

Acknowledgments

Superintendency of Archaeology of Latium and Etruria and specially to arch. Silvano Tanzilli, Director of the Museum and Archaeological Area. Professor Rodolfo M. Strollo, head of LAREA Laboratory of Survey and Architecture, Engineering Area University of Rome ‘Tor Vergata’, participated in the research. Engineers Laura Rossi and Emanuela De Feo and architect Wissam Wahbeh collaborated in the research with the student Roberto Di Maccio. The SAPR for aerial photography were made available with full liberality by Federico De Simoni (Quadricopter DJI Phantom 3) and by the company Georilievi Impei S.r.L. (Esacopter Aibotix X6 V2) with the collaboration of engineer Giuseppe Sini.

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A Multidisciplinary Project for the Study of Historical Landscapes: New Archaeological and Physicochemical Data from the 'Colline Metallifere' District

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Abstract
In this paper we will present some results obtained by a combined multidisciplinary approach to the study of a territory located in the southern part of Tuscany, the 'Colline Metallifere' district. The area has been studied from different points of view, and there are many written contributions concerning the evolution of its human landscape over the centuries. In this paper we are focusing particularly on the use of chemical analyses on crucial historical areas. The considerable amount of information retrieved and the unquestionable value of the data obtained by portable X-ray fluorescence (pXRF) analyses are now opening new fields to the use of the portable instrument. The new opportunities offered by the 'NeuMed' ERC project, based in the University of Siena, will allow the testing of the reliability of this technique on a wider scale, in multidisciplinary research that aims to reconstruct the historical landscapes of the area.

Keywords: interdisciplinary methodology, archaeological surveys, physical-chemical analysis, pXRF, mining territories

The Colline Metallifere district: a multidisciplinary open air laboratory (L.D.)

In recent years, the Colline Metallifere district (southern Tuscany) has become a multidisciplinary study area in which a combined archaeological, geological, and environmental approach is providing new and interesting evidence for the reconstruction of historical landscapes. The territory is very well known from the numerous research projects undertaken over the years on archaeological and historical targets and mining deposits (Dallai and Francovich, 2005). The hills which give the area its name cover part of Livorno and Grosseto provinces; the territory includes the coast and the immediate hinterland of the Gulf of Follonica, an important working hub for the iron oxides (hematite) that have been exploited on Elba Island since the Etruscan period.

Ever since that period, the entire area has been historically very important for mining activities. During the medieval period in particular, the exploitation was especially focussed upon mixed sulphides deposits of copper, lead and silver; the consistent ore bodies were worked in order to obtain the metals needed for coin production.

These rich deposits and their exploitation attracted the interest of important aristocratic families, which, since the central centuries of the medieval period, developed their control over the underground resources through fortified settlements placed close to the mining fields. The archaeological research undertaken since the 1980s and the excavation of 'mining castles', such as the well-known castle of Rocca San Silvestro or the castle of Rocchette Pannocchieschi, have demonstrated that the development of local lordships in this geographical context was deeply linked to the control and exploitation of metals that could be used for coinage (Bianchi, 2010).

Since then, a large number of research projects have been carried out with the aim of studying the possible relations between settlements and mineral resources, with particular reference to settlement patterns and the control over the cycle of production through the centuries. Extensive surveys on territorial samples have been carried out in order to define the main aspects of mining exploitation and metal production; the data collected has been processed with the aim of defining a broad picture of the territory, both from an archaeological, geological and environmental perspective (Benvenuti *et al.,* 2014).

Out of this wide territory, specific targets have been selected for a multidisciplinary research; these 'pilot' studies started with in-depth research carried out on mining fields (particularly in the mining areas of

Figure 1. Location of sites mentioned in the text.

Serrabottini and Niccioleta, close to Massa Marittima, Grosseto province). In order to get the maximum amount of useful information, a combination of underground surveys, fieldwork and XRF analyses on water-borne sediments and soils have been planned. The data collected has clarified the technical characteristics of the production and the environmental impact of ancient mines on the surrounding area. Finally, chemical analyses carried out on waste material has revealed a skilful selection operated at the mine head in order to eliminate useless minerals, zinc in particular (Aranguren *et al*., 2007; Dallai *et al*., 2015a; Dallai *et al*., 2013). A combination of underground surveys, fieldwork and XRF analyses on fluvial sediments and soils explored the technical aspects of the production and the environmental impact of ancient mines in the surrounding area (Aranguren *et al*., 2007).

The multidisciplinary approach has focused not only on territorial samples, but has also included the study of specific archaeological sites; some of which are medieval settlements located in the core of mining areas (that is the case of the church of San Niccolò, near Montieri); some are production sites (as for the alum production site of Monteleo, close to Monterotondo Marittimo); whilst others are sites based in the coastal plan, near the shore, that have been identified by archaeological surveys and remote sensing techniques and recently excavated (i.e. the Carlappiano site, near Piombino) (Figure 1). On all these specific places, as well as on other key samples that have been discussed in previous papers (Dallai *et al*., 2015b), a multidisciplinary approach has been first planned and then undertaken directly on site. Finally, the obtained results have been examined and analysed in order to obtain increased information. The final goal of our project is, in fact, to provide an historical and environmental landscape reconstruction based on multidisciplinary data sets; merging historical data with chemical-physical results we are gradually adding crucial pieces of information to the picture of one of the most important mining district of the Mediterranean area.

From the different case studies, by combining archaeological and physico-chemical data (pXRF in particular) we are gradually building up a solid database that is helping to define the historical outlines of the Colline Metallifere landscape. Moreover, building upon previous research experience, pXRF analyses are now playing an essential role in the research strategies of the 5 year ERC project *'NeuMed Origins of a new economic union, 7th–12th centuries: resources, landscapes and political strategies in a Mediterranean region'* based in the University of Siena (P.I. Prof. Richard Hodges). The reconstruction of the historical features in the landscape becomes crucial to understand the deep changes that occurred in settlement patterns, trade routes and economical background of the area between Late Antiquity and the 12th century.

Investigation methods (V.V., A.D.)

Physico-chemical analysis of different environmental matrices is becoming a fundamental tool for multi-scale archaeological prospections. From the enrichment or depletion of certain elements or molecules in soil, stream sediments, groundwater etc., their spatial distribution and their statistical treatment gives the chemical fingerprint of a territory with possible genuine correlations with ancient human activities (Oonk *et al*., 2009; Anguilano *et al*., 2010).

Recently, pXRF has been used for the quantification of major and minor elements in soils, stream sediments and artefacts, and it emerged as the elective technique for *in-situ* analysis. In fact, the pXRF instrument can be directly used on the surface of untouched environmental matrices and immobile artefacts. It can be also used for laboratory analysis with treated (dried, milled, sieved) samples. The major features of pXRF analysis are the non-destructive nature of analysis, the speed of operations, the capability of on-site measurement, and the immediate availability of analytical results (Potts and West, 2008; Shugar and Mass, 2012). The protocol can be used in multi-scale investigations (*in-situ* and medium-large territorial scale) with both predictive and descriptive goals using slightly different techniques.

In-situ studies were conducted collecting data using a pre-determined grid frame of 1 m^2 (1 m × 1 m) areal elements. Inside each areal element the concentration of a chemical species was given by the average of three single pXRF measurements (Dallai *et al*., 2015a). Depending on the required sampling density, the number of pXRF sample points in one of areal element could be much higher, often following the concurrent excavation of single units. In this context the measurements done directly on archaeological finds or archaeological structures (architectural elements, furnaces, walls, mortars, slags etc.) can also be included, which is a great help for their functional characterisation.

In the medium-large territorial scale the sampling density is lower and usually follows the geomorphological elements of the territory. The fluvial stream sediments were proven to be the most useful environmental matrix for studying the chemical anomalies due to ancient industrial settlements. This because the streams and rivers are the collector of the contaminated material originated by one or more different sources within their own drainage basin. In particular, the production activities exploited in this mining area can be traced in detail from the extraction of the mineral ores to the smelting and refining of the metals.

Figure 2. pXRF laboratory station.

On the other hand, the ancient mining field can also be investigated spatially and directly. In this case, the concentration of elements in geo-referenced soil samples gives the chemical fingerprint of the area.

Both laboratory and on-site pXRF analysis were performed using an Olympus DELTA-premium handheld pXRF analyser, equipped with a 40kV tube, a 'large area SDD detector, accelerometer and barometer for atmosphere pressure corrections for light elements measurements. The laboratory measurements were done with the instrument mounted on a fixed station (Figure 2). To ensure the quality of the data obtained, operating protocols was used (EPA, 2007). All laboratory samples were collected in the same spot as the on-site measurements; they were dried at room temperature, sieved at 125μm and placed in the appropriate sample holders. Data were acquired with the 'Soil Mode' (3–beam) of the instrument which utilises Compton Normalization for low concentrations (PPM to 3%) of elements in light matrices. The result for each sample was the average of the three measurements. Chemical data was finally geo-referenced together with the archaeological information in a GIS application (QGIS) used to produce distribution maps.

Medium-large territorial scale (V.V., A.D.)

In this work we present the results obtained in two sites that have recently been investigated. One of them was the ancient Serrabottini mining area, and the other is the Monte Gai site; both of them are close to the medieval town of Massa Marittima. Here, the major activity was the extraction and processing of mixed sulphide ores for the production of copper. The chemical data collected in mining dumps areas confirmed the major

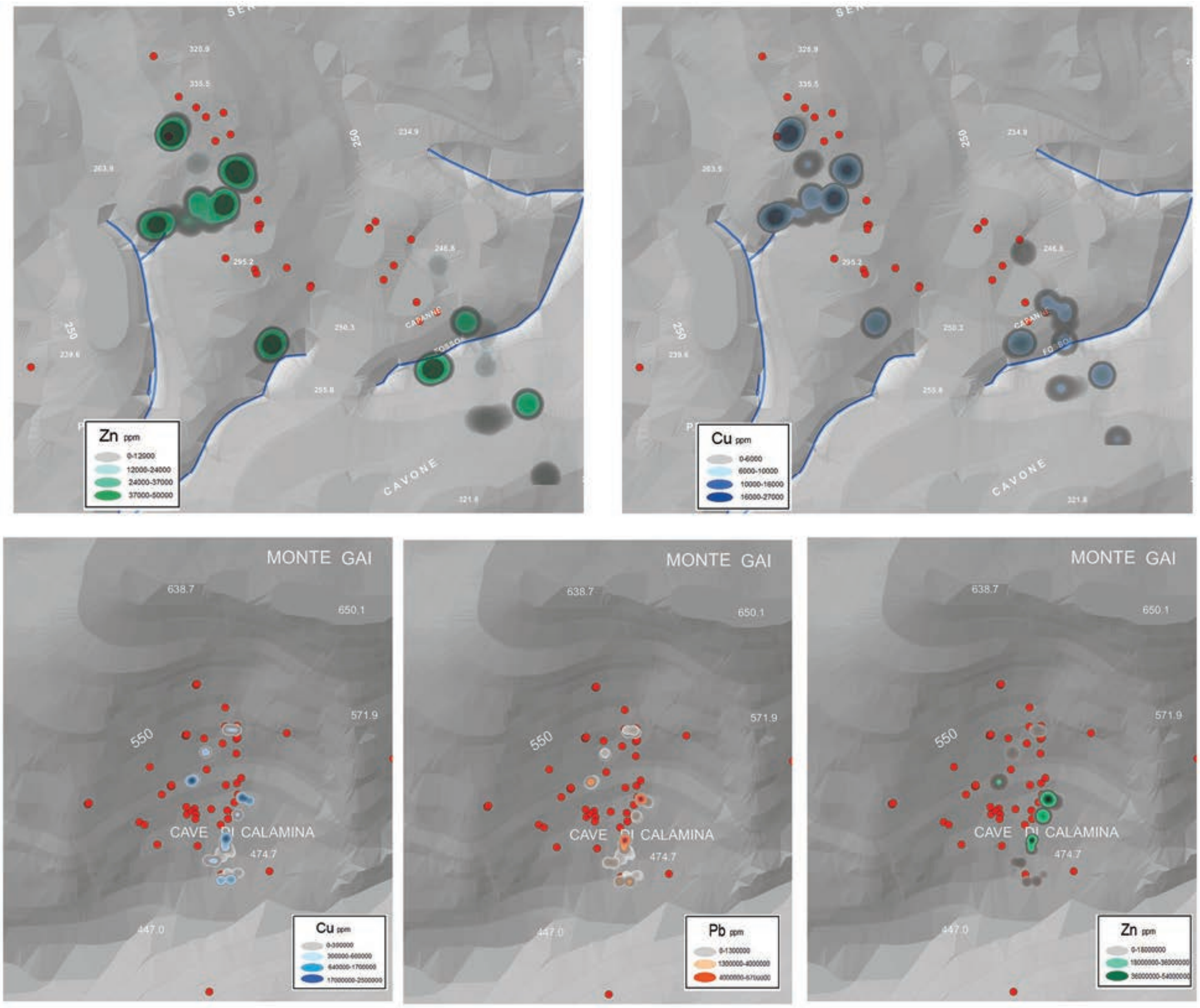

Figure 3. Serrabottini (Massa Marittima, GR). The chemical data collected through pXRF analyses on ancient and modern mining dumps have revealed the main goal of the ancient mining exploitation (particularly Cu), as well as the contamination of the soil.

goal of the exploitation (copper production) as well as the extent of heavy metal pollution and its diffusion. In the Figure 3, the concentration of Cu, Zn and Pb are reported on the map of the site, showing the position of the large mine tails dumps that are located in a strategic position with respect to the extraction sinks (red circles). The data also revealed that the diffusion of the contamination is quite restricted to the sites and its spreading is poorly enhanced by the weathering of mining residues.

Regarding the Serrabottini site, a k-mean clustering analysis was also performed. In Figure 4, 'A' reports one of the ten different correlation diagrams obtained by the k-mean clustering, in which different colours represented samples that were grouped by chemical similarity.

It was noteworthy that by observing geo-referenced data on the site map (Figure 4B), a spatial separation of the clusters emerges. In fact, Cluster-1, with higher concentration of Cu, Zn and Fe was mainly restricted in two small areas with respect to the Cluster-2 data. This fact could be explained with the hypothesis that in these two areas a different production activity (namely roasting of mineral ores) was accomplished. Cluster-3 was constituted by only two samples with very high lead concentrations.

This result can also be explained by considering that during the first phase of the metallurgical process for copper production, the roasting of mixed sulphide ores, induced a large loss of the most volatile metals: arsenic, antimony and lead; while zinc was not completely lost in this phase. To eliminate almost all impurities and zinc, after the roasting, a preliminary phase of smelting

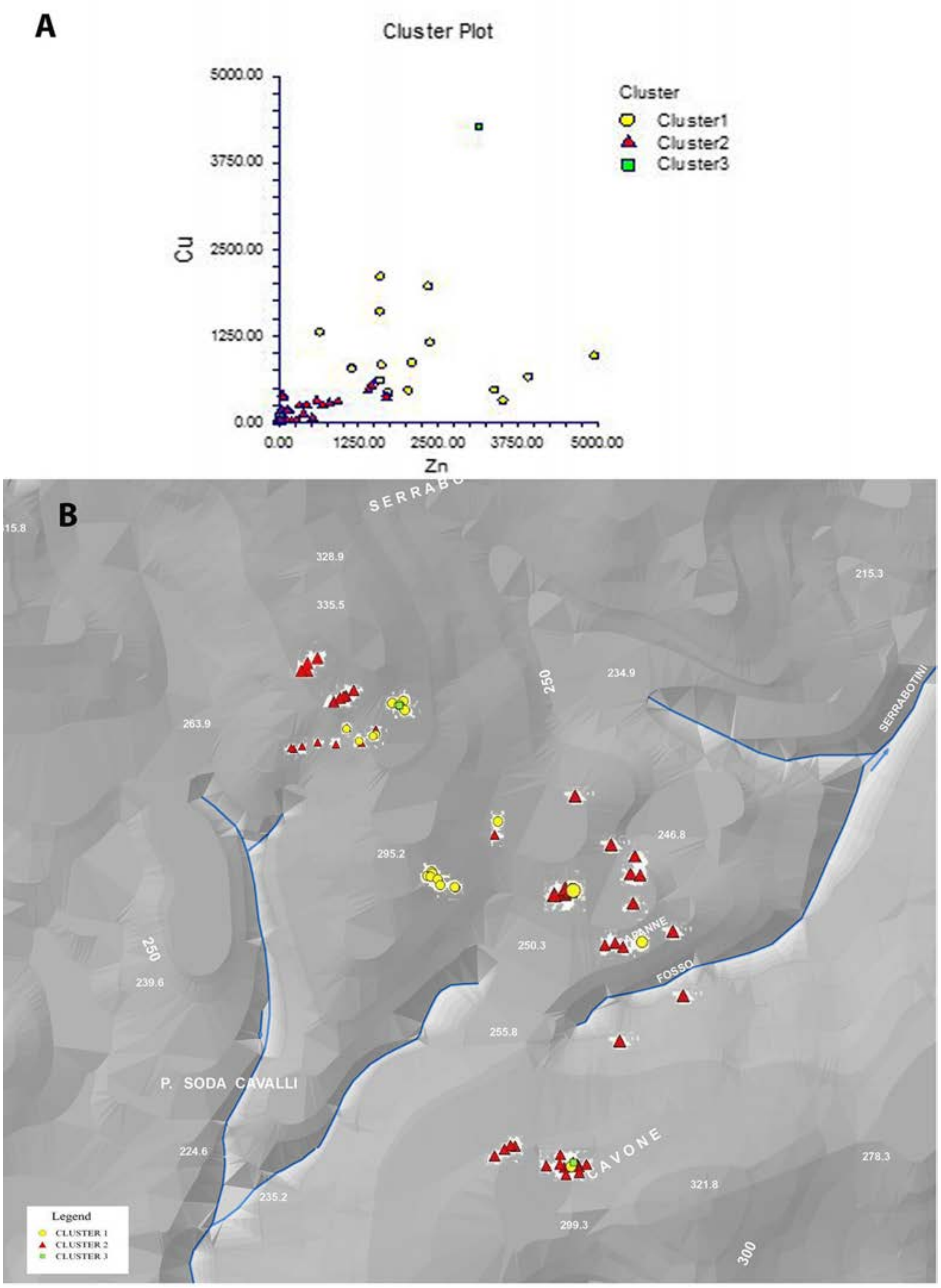

Figure 4. Statistical treatment of the data (K-means clustering analysis). In Figure A the correlation diagram of Cu-Zn; in Figure B, the georeferenced data on the site map.

produced a copper matte that was roasted a second time before the final smelting.

In-situ analyses and results (L.D., A.D., V.V.)

Regarding *in-situ* investigations, here we present three key sites showing relevant data, with interesting connections to the archaeological evidences: the 'Canonica di San Niccolò' site (Montieri — GR); the 'Allumiere di Monteleo' site (Monterotondo Marittimo — GR) and the Carlappiano site (Piombino — LI).

'Canonica di San Niccolò' *(Montieri — GR)* (L.D., A.D.*)*

Montieri district has been one of the most prominent silver, lead and copper mining areas of the Colline Metallifere. It was certainly at the heart of a complex system of ore-working and mineral production, probably connected to the activities of the neighbouring castles. Its' importance is documented by the presence of a mint which, between the end of the 12th century and the first half of the following century, struck coins on behalf of the Volterra bishop.

Figure 5. The intra-situ pXRF analyses at the Canonica site; the sampling grid.

NW from the village, on the slopes of the so called 'Poggio', a systematic set of analyses have been carried out on the archaeological site of the Canonica di San Niccolò (a parish church), a peculiar church building with six apses, with adjacent spaces and buildings dedicated to different activities. The documents attest the existence of the site from at least 1133, while the dig provides evidence of an initial occupation of the terraced site probably in the period between the 9th and 10th centuries. The final abandonment of the site occurred just before the 15th century (Benvenuti *et al.*, 2014).

		Fe (mg/kg)	Cu (mg/kg)	Sn (mg/kg)	Pb (mg/kg)
Area 2000	average	43601.2	64.7	19.7	69.4
	st. dev.	10101.1	73.3	23.5	50.2
	min	12161	10	1	19
	max	97993	898	239	371
Area 3000	average	36234.4	37.7	19.3	57.9
	st. dev.	5821.2	11.5	17.6	36.0
	min	11567	5	1	20
	max	59584	66	81	346

Table1. Comparison of simple statistic parameters for Fe, Cu, Sn, Pb data obtained in the Canonica area (Montieri — GR).

At the Canonica site, a very large sampling grid frame of 1 m^2 was applied, covering a large part of the excavation area (AREA 3000 and AREA 2000) (Figure 5). The chemical elements for this type of analysis considered as significant 'tracer' elements, useful to identify archaeometallurgical production, are Pb, Fe, Cu and Sn.

Simple statistic parameters for Fe, Cu, Sn, Pb data regarding the Canonica site showed lower values for AREA 3000 with respect to AREA 2000, both for averaged and peak values (Table 1). This fact indicates that different activities were carried out in the two parts. AREA 3000 had principally an agricultural function whilst AREA 2000 was a production area where different types of craft activities were conducted. In this area the excavation campaigns had already identified the remnants of forging activities and other production evidence.

A more accurate analysis was obtained by observing the spatial distribution of the metal concentrations (Figure 6). In the western part of AREA 2000, the higher concentrations of Pb and Fe confirmed the presence of a forge, while in the centre, high values of Sn and Cu

Figure 6. Results of intra-situ pXRF analyses. The ring circumference is proportional to the concentration of the considered chemical element. Analyses have highlighted high concentrations of Sn (A) and Cu (B) on the centre of the area 2000.

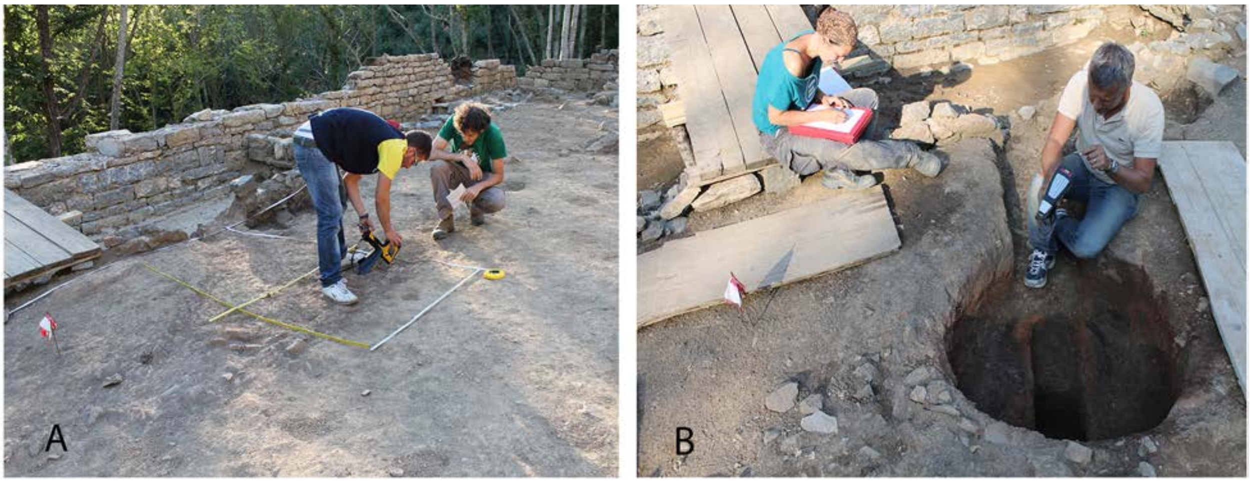

Figure 7. pXRF analyses have been used for both descriptive and predictive goals. In Figure A the intra-situ analyses before the discovery of the bell-kiln remains (Figure B) (credits: LTTM, University of Siena).

identified the presence of an activity linked with the use of an alloy of these two metals. The subsequent dig campaign discovered the remains of a bell-kiln located exactly in the area of the pXRF anomaly (Figure 7, Dallai *et al*., 2015a). No evidence was found regarding the anomalous presence of Pb related to the silver production.

In this case, the *in-situ* analysis has confirmed and demonstrated the reliability of this technique and the descriptive and predictive power for the study of archaeological sites with a production 'vocation'.

The reported study performed at the Canonica of San Niccolò, was a part of a wider project started few years ago in order to understand the productive history of the small medieval village of Montieri, one of the most important silver extraction sites during the Middle Ages. Previous investigation took into account the metal concentrations in the stream and river sediments of the area. Using the approach on medium-large territorial scales, a wide range of information about ancient mining, roasting and smelting activities was obtained for the area around the village (Dallai *et al*., 2015a). Contrary to previous work, the rivers around the Canonica did not present evidence of metal contamination. In summary, the combination of physico-chemical and historical analysis have been definitely useful to understand the nature of the metallurgical activities undertaken near the village of Montieri, as well as to detail the nature of working activities that took place at the Canonica site. In this case, the absence of metal processing evidence

Figure 8. The battery of the early-modern alum furnaces at the Monteleo site. The red ring indicates the area where pXRF analyses were conducted.

excluded its direct involvement in the silver economy, which was the most particular feature of the area during the medieval centuries.

'Allumiere di Monteleo' (Monterotondo Marittimo — GR) (L.D.)

The Monteleo alum works are located in the NW reaches of the Monterotondo Marittimo municipality and extend along the two banks of a local stream, the waters of which played an essential role in numerous steps of the production process (Dallai, 2014). From an archaeological point of view, the discovery of this site and of a non-metallic working cycle in the Colline Metallifere district dating to the late medieval period, such as the alunite one, has enlarged upon the already detailed evidence of pre-industrial extraction activities in the area, which until now referred almost exclusively to the cultivation of mixed sulphides.

The raw material worked in this site is alunite, an aluminium potassium sulphate ($Kal_3(SO_4)_2(OH)_6$) that is practically insoluble in the natural state. Nevertheless, it is possible to transform alunite into high quality alum through a process of roasting, maceration, leaching and crystallisation known since medieval times and described in detail in two renown 16th century technical treatises: *De la Pirotechnia* by the Sienese, Vannoccio Biringuccio published in 1540, and *De re metallica* by Giorgius Agricola, published in 1556: to date, detailed reconstructions of the technical procedures and tentative functional interpretations of known material finds have mostly been based on these descriptions.

There are currently only a few but significant case studies on archaeological sites linked to the production of alum from alunite, and Monteleo is one of these. The excavation, begun in 2008 by the University of Siena, is providing important new information on adopted technologies. Most of the structures which have been brought to light may be ascribed to the so-called 'Renaissance phase' of the site, i.e. to between the end of the 15th century and the first half of the 16th century, a period of documented renewal of alum mining and processing in numerous areas of Tuscany (Boisseuil and Chareille, 2009) (Figure 8).

Despite the written sources, the archaeological investigation revealed a longer history on the site, with evidence of production activities starting much earlier than the 15th century. The remnants of wall structures in irregular limestone blocks bonded with soil, most likely relating to a furnace, refer to this earlier period and were obliterated by the 16th century masonry of the alum works. Radiocarbon dating performed on different charcoal samples have proven that the furnaces occupying the terrace, as well as other productive structures and forges identified on the site, were used in the late 13th century.

In-situ pXRF analysis (i.e. analysis planned inside a single archaeological site), were conducted during the excavation campaigns in order to understand the kind of production related to these ancient remains. Whilst on the Canonica site the pXRF analysis was conducted principally on the soil, at Monteleo this technique was also applied to the remains of the productive structures, as well as on finds (slags and metal droplets). The pXRF analysis, in particular has identified former metal production involving copper and silver sulphides. Data analysis showed the presence of high anomalies of Cu (2000 mg/Kg) and Fe (3000 mg/Kg) in specific and restricted areas of the site, linked respectively to a copper furnace and a forge (Figure 9). The pXRF analysis of several metallic fragments and residues from several stratigraphic units show high concentrations of S, Ca, Cu, Fe, Pb, Sn, Zn and Ag; copper is always present with high concentrations (60 wt%) (Dallai and Volpi, 2015).

Carlappiano (Piombino — LI) (V.V.)

While the previous examples proposed have shown the high potential of analyses performed on archaeological excavation and territorial samples, new research perspective are now open to a multidisciplinary approach within the frame of the ERC Advanced European Research Project *Neumed,* mentioned above. The project, started in October 2015, has selected the first targets on which archaeological excavation as well as environmental analysis have been planned and the Carlappiano site is one of these. Prior to the dig, remote sensing (i.e. magnetometer, drone and historical aerial photographs analyses) as well as pXRF measurements have been carried out, providing promising initial results. The site is located on a dune close to the shore

Figure 9. At Monteleo (Monterotondo Marittimo, GR), a late medieval alum productive site, pXRF analyses and archaeological data have identified a former metal production involving copper and silver sulphides. In Figures A and B, the archaeological remains of the late 13th century productive phase. In Figure D, the pXRF analyses indicates the presence of high concentrations of copper (credits: LTTM, University of Siena).

line, on the boundary of what once was a coastal lagoon, not far from the city of Piombino. From historical aerial photos, a dry area of about 8 ha surrounded by a dark almost circular sign was clearly visible. The analysis of 19th century historical cartography allowed us to recognise a hydrographic system composed of two different streams, which met exactly at the height of the dune, very close to the site, and lead to the sea with a seemingly large mouth.

The pottery and finds collected on the surface offered a wide chronological range: some were dated to the Bronze Age, many others could be referred to the Roman periods (imperial and late antique), and to the early medieval (ca 9th AD) and central medieval centuries (13th–14th) (Dallai *et al.,* 2003; Marasco, 2013).

Analyses using pXRF were performed on the Carlappiano area, by using both on-site and laboratory methods. The on-site analyses were conducted both inside and outside the anomaly previously observed by aerial images (interpretation of vertical historical coverage, 1938–2015). For this investigation, a particular sampling strategy was developed. Six transects, with North — South direction were investigated, having one measurement every 20 meters; some measurements were taken also in the area surrounding the site. The chemical elements analysed were As, Cu, Zn, Fe, Ca and Pb (Figure 10). It is noteworthy that the element distribution showed the presence of two different soil compositions, and that the separation line between them corresponded almost perfectly to the aerial anomaly boundary. A hypothesis is these differences could be related to the function of the settlement that the archaeological excavation has linked to salt production (Dallai *et al.,* in prep).

Conclusions (L.D., A.D., V.V.)

The use of pXRF on archaeological contexts is gradually gaining credit, given to the amount of case studies that are providing new evidence for the reliability of this technique. The multidisciplinary approach developed in the Colline Metallifere project and the data collected,

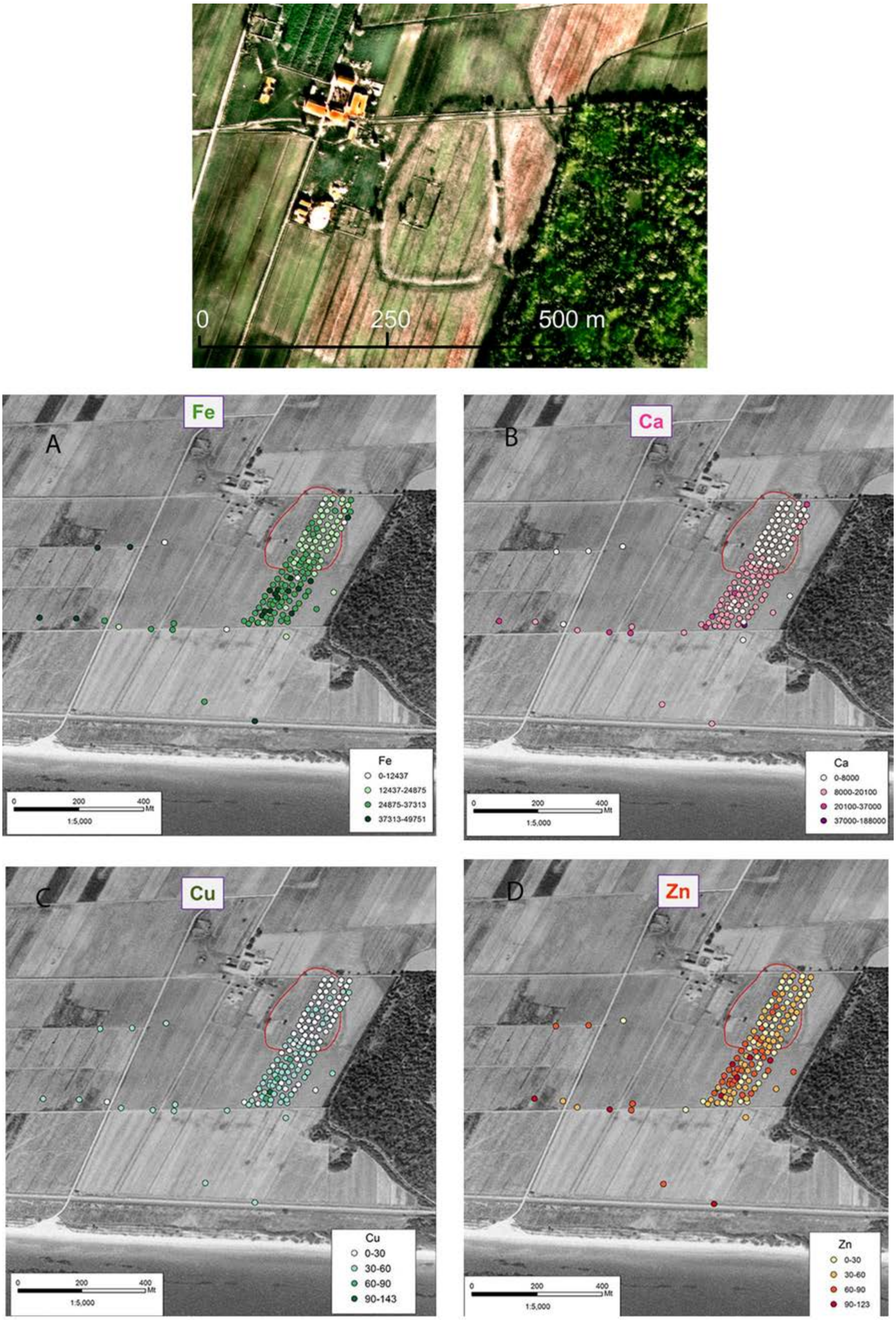

Figure 10. On the Carlappiano site (Piombino — LI), the archaeological dig has been anticipated by a multidisciplinary strategic approach, in order to map archaeological remains and relic landforms. These were visible both on-site (air photo interpretation of vertical historical coverage, 1938–2015) and in the surrounding area. In particular pXRF has highlighted how the roundish shape corresponds to an effectively different soil composition. In Figures B-E: Fe, Ca, Cu and Zn concentrations and in the legend are the concentration range considered for each element.

that we have briefly presented, demonstrate that pXRF can greatly help in understanding the nature of activities carried out on ancient sites, as well as defining the use of productive structures and entire territories. Moreover, the proper use of pXRF techniques and the careful evaluation of the analytical results based on the co-operation of different research expertise, can not only describe the environmental and historical evidences, but can be used as a powerful predictive tool which can drive the research.

Through the combination of different data sets, including those that can be obtained from pXRF analyses, the reconstruction of historical landscape can definitely be more detailed; the amount of measurements that can be performed by the user-friendly pXRF has to be considered as an advantage on wider scale projects, like the one we have described. From the consistent experience gained with the multidisciplinary study of the mining territories of the Colline Metallifere we can now experiment with the potential of pXRF on different kinds of sites, such as the coastal ones selected by the NeuMed ERC project, along with Carlappiano, which is provided the first, promising case study.

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From Survey, to 3D Modelling, to 3D Printing: Bramante's Nymphaeum Colonna at Genazzano

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Abstract

Today, new computer techniques are increasingly employed in archaeology. Such techniques, organised according to a proper pipeline, allow a fuller knowledge of archaeological assets. In the study of the Nympheum Colonna at Genazzano, attributed to Bramante, an integrated approach to technologies like photogrammetric survey, 3D modelling, virtual tour and 3D printing, enables a scale reproduction of the image of the Nymphaeum at the beginning of the 16th century. First, data are acquired through a total station; the second phase consists of georeferenced photo shoots to obtain bitmap textures that can be subsequently used in modelling and rendering as a complement to three-dimensional data. During the final step, the virtual model is transformed into a prototype by means of 3D printing. Such methodology increases the 'empathetic dimension' with the archaeological asset, making it more enjoyable and better perceived both in its current state and as a historical reconstruction.

Keywords: survey, Bramante, reconstruction, 3D model, 3D printing

Introduction

Technology-related archaeological research has had a limited development, since technological innovations in the field of documentation can hardly find shared forms to communicate the manifold experimental initiatives in this field. In this context, a hot discussion topic is three-dimensionality; this problem is inherent in the survey of any structure characterised by its planimetric development and depth. In particular, in the field of architectural survey and archaeological reconstruction, the debate revolves around new technique's no contact survey or 3D shape acquisition techniques, used as tools of investigation and archaeological and architectural knowledge. However, as it often happens, the technological evolution is not applied as rigorously as it should: with this type of survey, the three-dimensional coordinates do not always describe the object perfectly and the result is not always consistent with the objectives to be achieved. Our work and research stem from these assumptions. Our objective is the development of a simple and consistent methodology. This latter point simultaneously uses historical investigations, theories and technology applications in order to draw up a model of the examined reality and its possible historical evolution with an eye to an easier communication and enjoyment.

Case study

To achieve an integrated and univocal approach, our methodology was applied to a case study: the Nymphaeum Colonna at Genazzano (Figure 1). Genazzano is in Lazio, Italy. It is a town of six thousand inhabitants, about 50 km south–east of Rome. Its historical importance is due to its location (it was a focal point connecting Rome to southern Italy) and to its link with the Colonnas', including Pope Martin V, who turned Genazzano into a papal fortress (Mariano and Panepuccia 1985; Senni, 1838).

The structure in question is located outside the historic centre of Genazzano, south–east of the town, in the valley of the river called Il Fossato. The artefact extends for 48 meters in width and 18 meters in depth, with a height of about 12 meters. Its main element is the loggia, a three-bay construction facing on the east side, where the main façade and the old entrance are located.

This space is separated by an apsed room with three Serliane, characterising the structure. The south and north sides of the loggia open onto an exedra, consisting of three niches. A passage located in the central niche leads to two rooms, to the north and to the south. The latter area is where the current entrance is located. Finally, as the floor plan shows, two more rooms are located to the north and to the south. From south, one can enter the apsed room behind, thanks to a staircase built at the beginning of the twentieth century, approximately one meter above the loggia. As to the north room, only some ruins remain following a collapse.

The north side is home to a special building, the so-called 'Octagon'. Inside, it accommodates a circular

Figure 1. Main facade, Nymphaeum at Genazzano. Author's photos.

(Figure 2. Choir of Santa Maria in San Satiro, perspective. Author's photos.

basin which in the past was used to receive rainwater and for water games. It was this building that gave the name Nymphaeum to the structure; due to its configuration, scholars have mistakenly assumed it had been built in Roman times. The special shape of the structure and the lack of documentary sources concerning the original project construction, meant the identity of the place was lost over time, make the commissioning, function (Cazzato *et al.*, 2001; Colonna, 2009, 2010), construction and author uncertain.

The central part of the Nymphaeum, dating from the first decade of the sixteenth century, was attributed by many scholars to Bramante or some of his disciples (Borsi, 1989; Bruschi, 1969; Frommel, 1969; Giovannoni, 1923; Thoenes, 1974). Bramante, a leading artist during the Renaissance, worked in Milan, Rome and other major Italian cities. He first developed pictorial activity, exploring the rigor of perspective and the creation of an illusory space. It is for this reason that he applied pictorial illusionistic principles to architecture, such as in S. Maria in San Satiro in Milan, where the narrow surface behind the apse forced Bramante to simulate a space for the choir that did not exist. He got a sense of depth through reliefs and terracotta mouldings that he subsequently painted to create a perspective (Figure 2). In Bramante's works, the means of the painter and those of the architect are often interchangeable: his architecture became painting through colour and light techniques. This can be noticed in the Nymphaeum, where various perspective tricks simulate depth: the outline of the entablature of Serliane is not the same as the blinders of the piers, so as to make the plane of Serliane farther away from the viewer's eye (Figure 3).

Bramante's works are characterised by a law of proportioning which guides his whole design, both in terms of planimetry and elevation. In the Nymphaeum, the structure is based on a circular module determined by the distance between the bays of the loggia, equal to 14 Roman palms. His interest in the Roman world, its structures and proportions, were a common feature in Bramante's expression. Thanks to such proportions, it was possible to reconstruct, at a later stage, the height of the columns and the pediment of the main eastern façade.

Figure 3. Entablature profile. Author's photos.

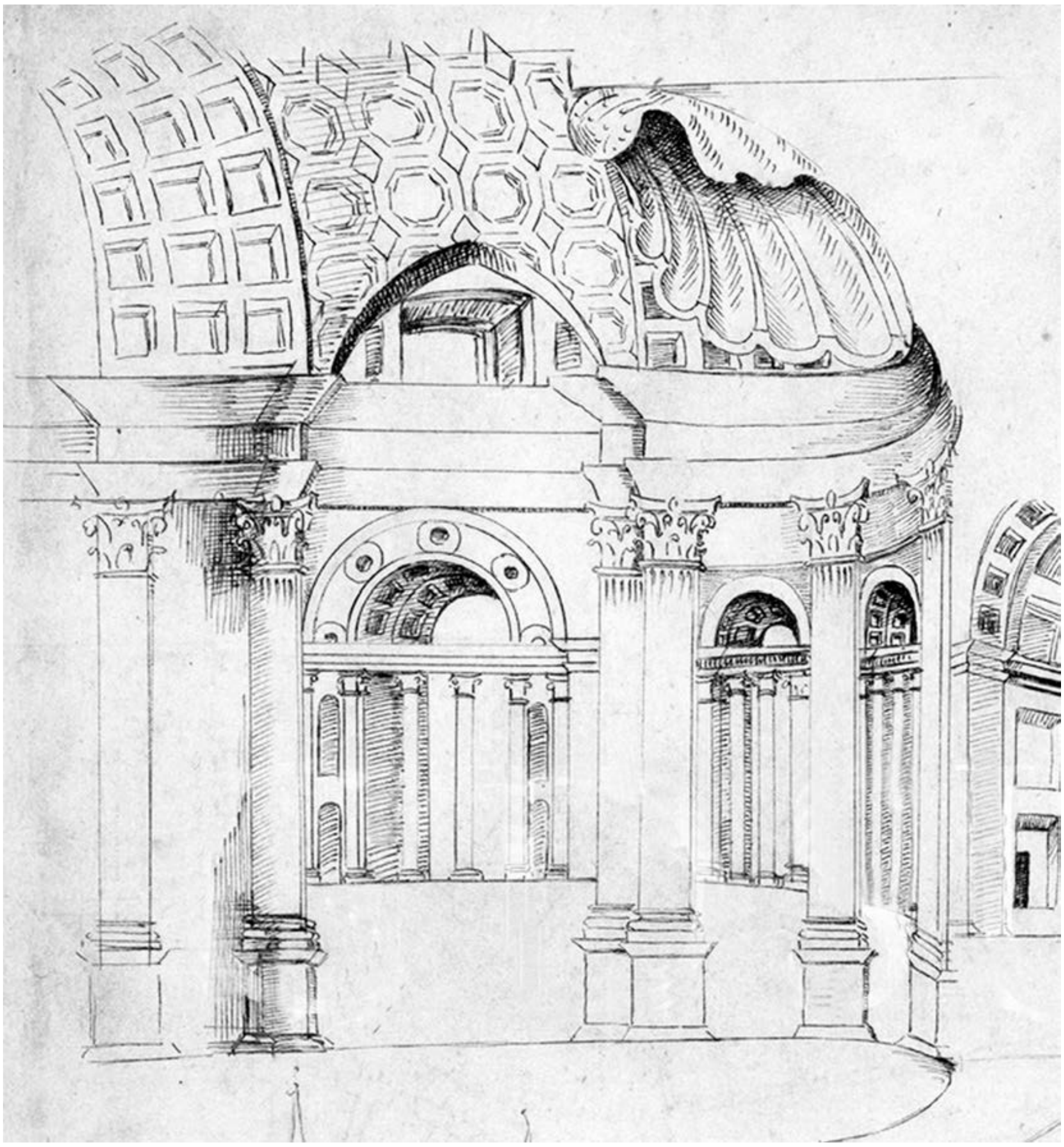

Figure 4. Choir of St. Peter in Bramante's drawings, Uffizi gallery, Florence, Italy.

The first project for St. Peter was drawn up by Bramante. Here, the interiors were hierarchically arranged. The same plan shows a new way of conceiving space, with special regard to the relationship between spaces and structure, between voids and masonry: in Saint Peter in the Vatican, as well as in the central part of the Nymphaeum, the structure seems to be conceived on the voids themselves. These take on a positive meaning juxtaposed to a negative masonry, modelled by the vacuum itself: exedras and niches follow one after another in a very smooth movement (Frommel, 2003)

Other aspects of special significance for planimetry, in addition to the perspective tricks and the geometric concept of the plan, remind us of Bramante style inside the Nymphaeum. These are: the octagonal planimetry, the double arch and double pilaster strip in a rhythmic play, giving more depth to the plane of serliane than the they actually are (serliane adorned by oculi are visible in Bramante's project for the choir of St. Peter) (Figure 4), the conscious use of the Tuscanic order (Ackerman, 1983; Rossi and Rovetta, 1999), often confused, at the time of Bramante, with the Doric. Bases and capitals of the Nymphaeum are entirely similar, both in shape and proportions, to those of the helical staircase of the Belvedere and the window of the Throne Room in the Vatican (Barucco, 2000a, 2000b).

Recent solution

In addition to the client, circumstances of construction and author, even the original shape of the building is unknown. This lack is a serious difficulty for scientific and geometric reconstruction, as well as the scanty documentary data concerning the original project. This has led to assumptions regarding the façade of the building. Such assumptions are not just referred to Bramante, but to a later period, when the artefact had already been modified. Many scholars presented hypothesis concerning the main façade only (Bruschi, 2010; Pearson, 2012; Fasolo, 1964; Frommel, 2003; Borsi, 1989). Those reconstructions are quite fragmented and do not consider a number of aspects. M. Döring, in 1998, published a comprehensive three-dimensional research, although she did not assume any form of cover due to evident difficulties in terms of reconstruction (Döring, 2001)

In order to find a solution to these geometric difficulties, strict and consistent criteria were developed. After an initial survey, a three-dimensional model was printed, in an effort to get to a comprehensive knowledge and enjoyment of the archaeological asset in all of its aspects. This logical process and methodology, which will be illustrated in the present study, has been infrequently adopted in archaeology and few examples are currently available. This line of experimentation led the University of Macerata (Ribechi, 2015) to try and recover historical assets and disseminate information about them. They studied and performed a hypothetical reconstruction of the Cryptoporticus of the temple of Urbis Sage at Urbisaglia in Macerata, Italy. A further application was proposed by the Monfort University (De Montford University, 2014) with the 'Digital building heritage project'. In this latter case, researchers reconstructed the ancient shape and appearance of the windows of Tixal Hall in Staffordshire, England.

Today, in the field of cultural heritage, 3D printing is mostly used to remake and restore missing parts for the purpose of preserving them. This technique is used to reconstruct objects completely lost, of which only few fragments are left, in the reconstruction of ancient artefacts to use in museum exhibitions (Neumüller *et al.*, 2014), or to bring back to life destroyed buildings (Krassenstein, 2015) by printing and replacing any missing elements or structural parts. In the aftermath of the war and the destruction of Roman architecture in Syria, the Institute for Digital Archeology of London, in collaboration with UNESCO, has had the difficult task of recreating works of Roman times destroyed in Palmira by militias. To recreate perfect copies of the destroyed works, experts have studied and explored their original materials. They have used advanced robotic equipment, digital sculpture tools to create high resolution models and 3D printers to give a new life to such works. An interesting use of 3D printing in cultural heritage is epitomised by the Faculty of Architecture of the University of Florence: by integrating technologies such as laser scanning, 3D printing and augmented reality, they obtained a faithful reconstruction of the state of the church of Meryemana in Goreme in Cappadocia (Gira and Aliperta, 2015). After survey and virtual reconstruction, printing a prototype facilitates the fusion between the real and virtual world: the model can be scale framed on a tablet or smartphone screen to show a virtual representation of the artefact as it is . This virtual model was complemented with gigaphotos reproducing the wall frescoes existing inside the Church, thus involving the viewer in a faithfully reconstructed, surfable environment.

In this field, laser technology has a sure potential; in particular, it can be used as an analytical and knowledge tool aimed at the virtual reconstruction (Agnello *et al.*, 2015); yet, there exist few examples of prototypes printed from a 3D survey, both to document the current state of the object and its historical reconstruction. Conversely, no contact technology is widely used; it enables the acquisition of an indefinite number of points and data during survey: the system output is a point cloud that needs to be processed. It is a starting point to define polygonal (MESH surfaces) or continuous surfaces with all the logical and methodological problems that this process entails. Nonetheless, point clouds exhaustively describe the surveyed object and its actual state; on the contrary, a TST survey methodology allows us to select the significant points that characterise an object, eliminating any unnecessary data. In a virtual archaeological reconstruction, it is more important to go back to the initial shape of the object. This allows us to obtain the generating geometric figures while eliminating any interference due to the action of time upon the structure (this activity is easier since it starts with non-uniform rational basis spline (NURBS) surfaces). However, an appropriate, concrete solution is the adoption of survey methods integrating mesh models deriving from laser scanners with auxiliary NURBS surfaces and various detection methods, in order to go beyond the difficulties of any technology and obtain hybrid models suitable for the purpose (Cannella, 2015; Juan Vidal *et al.*, 2011).

Proposed solution

In this framework of multiple episodes and solutions, the present research consists of a collection of all these experiences to standardise an integrated approach solving geometrical problems in the analysis of archaeological assets. Also, it allows those assets to be better perceived both in their current state and in their historical reconstruction. Technically speaking, we use widely shared and commonly available tools. They are integrated to create a multi-disciplinary methodology. First, we focused on the historic and documentary research, analysing archive documents found in libraries or in the archives of the Superintendence. A thorough search of the historic evolution of the name

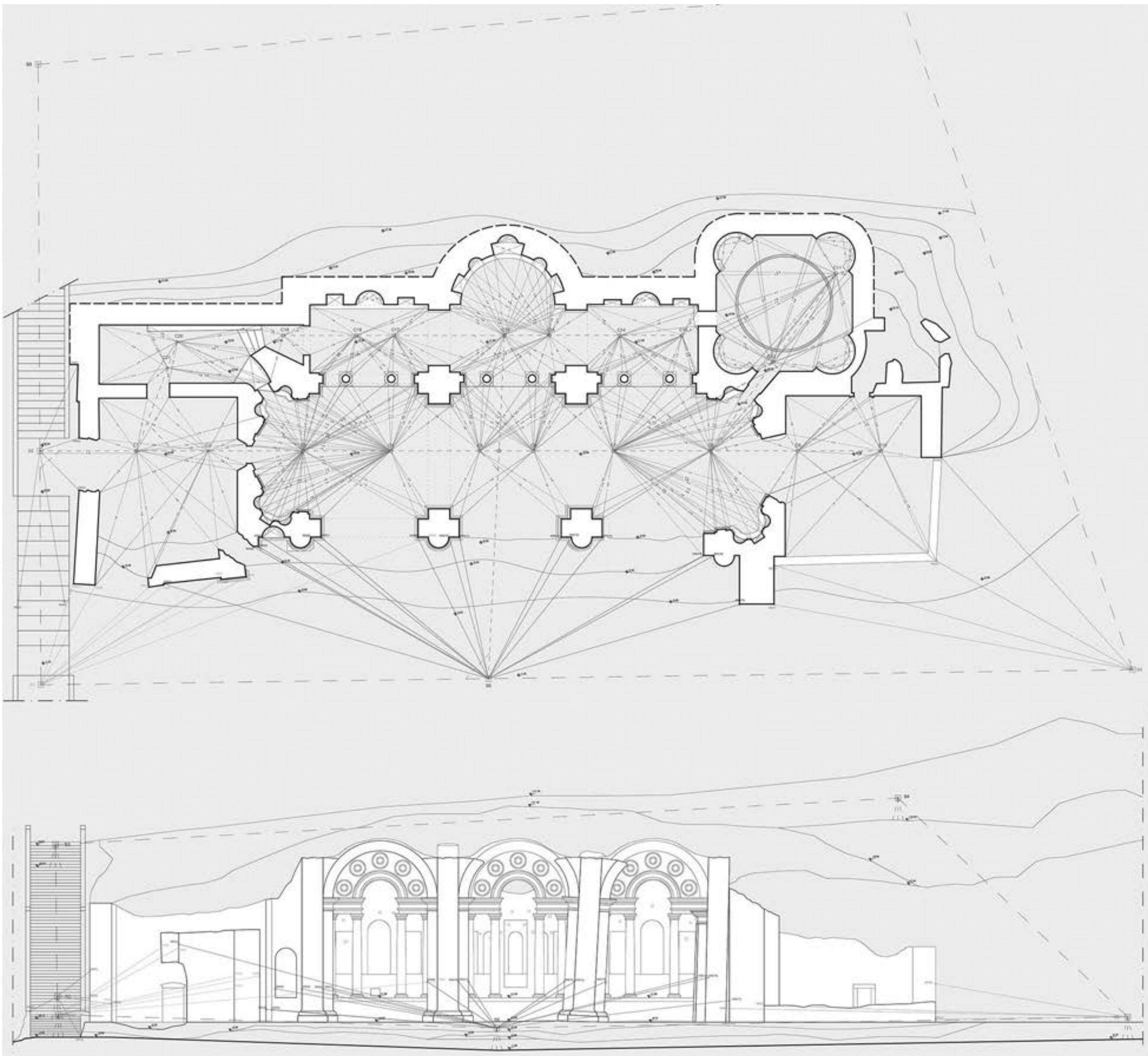

Figure 5. Plan and façade of Nymphaeum, surveying through total station. Author's photos.

Nymphaeum and its valley, led to the discovery of further items and to the awareness that the Nymphaeum was not a single, isolated piece of work. It was part of a compound located across the valley of the river Il Fossato. Furthermore, this work has brought to light a wall with the remains of a cement mortar layer. The structure forms an irregular base with projecting steps and can be likened to the substructures of a staircase. This has solved the problems of entrance into the building and to the area, raised by about 1.40 meters. The historical evolution of the structure, inferred and theorised by virtue of the documentary analysis, was then confirmed by archaeological investigations, conducted by M. Döring (2001): an analysis of structural cracks, remnants of the flooring, the existence of a flue, and a stylistic review (distinguishing the different periods of construction) led us to ascertain that the Nymphaeum was built in three different phases. The first phase cannot be accurately dated, but certainly goes back to the Roman age: the remains of flooring made of *opus caementicium* seem to imply that the walls of the current octagon rest upon a pre-existing circular structure. An archive search demonstrated the previous existence of some Roman baths or a place of worship dedicated to Venus (Matteini, 2009). Both the second and third phases date back to the 16th century, but are clearly distinguishable thanks to their proportions and to the structural settling cracks between the two buildings. The second phase of construction can be ascribed to Bramante, with the three central bays of the loggia, the apsed room and the octagonal space.

Our search continued with the acquisition of data through a total station. This tool works within a

S1	Horizontal distance	Position x	Position y	Position z	Angle	Vertical distance	Angle
0 100 (100)		100,0000	100,0000	1,2			
1 100 (1)	5,6538	101,7187	105,3863	0,4756	342	0,4756	285
2 100 (2)	6,0589	102,9163	105,3109	0,7044	331	0,7044	284
3 100 (3)	7,7519	105,7500	105,1990	3,6614	312	3,6614	303
4 100 (4)	8,4615	106,5803	105,3196	3,6564	309	3,6564	299
5 100 (5)	11,1325	109,6132	105,6142	2,1137	300	2,1137	282
6 100 (6)	12,422	111,0055	105,7608	2,1280	298	2,1280	281
7 100 (7)	11,1325	109,6132	105,7142	1,4572	301	1,4572	279
8 100 (8)	22,1585	120,7108	107,8784	1,18	291	1,18	275
S6	23,9556	123,9533	100,3327	-0,4839	271	-0,4839	268
S2	12,5171	99,9418	112,5170	1,0000	359	1,0000	357
S2							
0 200 (200)		100,0000	100,0000	1,2			
1 200 (1)	8,3316	98,8185	91,7526	0,4	172	0,40	289
2 200 (2)	2,9366	102,0712	97,9182	-0,10	225	-0,10	273
3 200 (3)	2,1781	102,0685	100,6821	-0,10	288	-0,10	273
4 200 (4)	5,0407	102,0587	104,5967	1,5863	336	1,5863	307
5 200 (5)	8,1887	101,3185	91,8182	-0,80	189	-0,80	211
S3	20,6864	99,9038	120,6861	8,3	359	8,3	259
S1	12,5171	100,0582	87,483	-1,00	183	-1,00	180
S5							
0 500 (500)		100,0000	100,0000	1,2			357
1 500 (1)	29,7566	71,0947	107,0668	1,5712	172	0,40	289
2 500 (2)	19,7763	80,9600	105,3455	1,1891	225	-0,10	273
3 500 (3)	12,0005	89,5036	105,8168	-0,1294	288	-0,10	273
4 500 (4)	15,4461	89,5036	111,3316	1,8111	336	1,5863	307
S4	38,5382	87,4486	136,437	11,9547	189	-0,80	211
S6	34,4750	65,5283	99,5212	-0,6017	359	8,3	259
					183	-1,00	180
S6							
0 600 (600)		100,0000	100,0000	1,2			
1 600 (1)	18,0944	82,6271	105,0585	4,5724	286	4,5724	285
2 600 (2)	14,3954	87,4486	107,0491	0,6884	299	0,6884	275
3 600 (3)	14,1670	87,7091	107,0456	0,6884	300	0,6884	275
4 600 (4)	14,2523	87,9091	107,5456	2,1338	302	2,1338	280
5 600 (5)	13,0460	89,3576	107,5456	2,1338	305	2,1338	281
6 600 (6)	12,1260	90,5076	107,5456	2,1338	308	2,1338	283
7 600 (7)	11,7006	91,0576	107,5456	2,1338	310	2,1338	283
8 600 (8)	8,4415	96,2076	107,5457	2,5275	333	2,5275	304
10 600 (10)	7,8304	97,9076	107,5457	2,5275	345	2,5275	320
11 600 (11)	7,7017	98,4576	107,5457	2,5275	348	2,5275	329
12 600 (12)	8,4786	103,8664	107,5457	2,5200	333	2,5200	304
13 600 (13)	8,7431	104,4164	107,5457	2,5200	330	2,5200	301
14 600 (14)	9,7133	106,1164	107,5457	2,5200	321	2,5200	293
15 600 (15)	13,0848	111,0076	107,0743	2,7421	303	2,7421	284
16 600 (16)	13,5508	111,5576	107,0743	2,7421	301	2,7421	283
17 600 (17)	13,9789	112,7076	105,8243	1,4921	395	1,4921	277
S1	23,9554	76,0468	99,6673	0,00	269	0,00	272
S5	34,475	134,4717	100,4783	0,00	271	0,00	271

Figure 6. System of coordinates of surveyed points. Author's photo.

system of local coordinates x, y, z. All coordinates are then translated into a system of absolute or geodetic coordinates. The surveying instrument measured all points defining the geometry of the various building elements, such as edges, corners, key arches, etc. (Figures 5 and 6). In archaeological survey, it is necessary to integrate automated surveying with the on-site observation and interpretation of the objects to be represented, by means of a direct survey: the points measured by the instrument were therefore printed at the desired scale, in plan and elevation view, on transparent sheets used as a basis for direct surveying. Thanks to CAD software (Autocad), coordinates were transformed into georeferenced points in a three-dimensional space. Such points can be displayed by the graphics software in different views: plan, façade or axonometric view. The indirect survey is then integrated directly into the software using data from the direct survey.

After obtaining the representation of the structure, we performed a series of comparative analyses of the planimetric plan, perspective and three-dimensional layout. By studying the philological structural elements, not only can one ascribe the Nymphaeum to Bramante but also compare it with buildings or drawings from the same period, so as to thoroughly understand its construction techniques and stylistic affinity. By comparing, for example, the architecture of the Nymphaeum with plans, facades and other drawings by Baldassarre Peruzzi (Britton, 2000) on exhibit at the Uffizi Gallery and the coverage of the loggia of Raffaello Sanzio's Villa Madama or Bramante's Santa Maria delle Grazie in Milan, we could hypothesise the shape of the Nymphaeum both in plan-view and in elevation. This hypothesis was later confirmed by the data obtained from the survey.

The metric surveying was then supplemented by photogrammetry. The photographs were taken in such a way as to get several frames of the most significant elements, recognizable in the coordinate system resulting from surveying using a total station. The image rectification software (RDF) is provided with a table to report the spatial coordinates obtained by the metric survey, i.e. the object coordinates; it then matches them with the x and y coordinates of pixels of the photographic image, i.e. the image coordinates. By combining traditional digital photogrammetry with HDR and spherical images, it is possible to reach sophisticated levels of exploration and accuracy, unlike two-dimensional photography. Furthermore, this type of virtual exploration is more readily understood by the general public (Figure 7). Finally, during the modelling and rendering phase, the actual state is reconstructed thanks to previously acquired data. By matching object and image coordinates, texture can be created: during the texturing step, colour images are mapped on the three-dimensional geometric surface, adjusting colour values and bump. After modelling the current status, different reconstructions are considered: in this case, given its complex geometry, it was possible to analyse and develop the most suitable solution for the architecture of the structure. This result was obtained thanks to the geometric accuracy of the acquired data, their manipulation and processing through mathematical surfaces and NURBS, and the possibility of calibrating coordinates via control points. On the digital model, heights and distances can be measured; surfaces and volumes are calculated by automatically extracting vertices, edges and faces that are encountered in the shared edges (Figure 8).

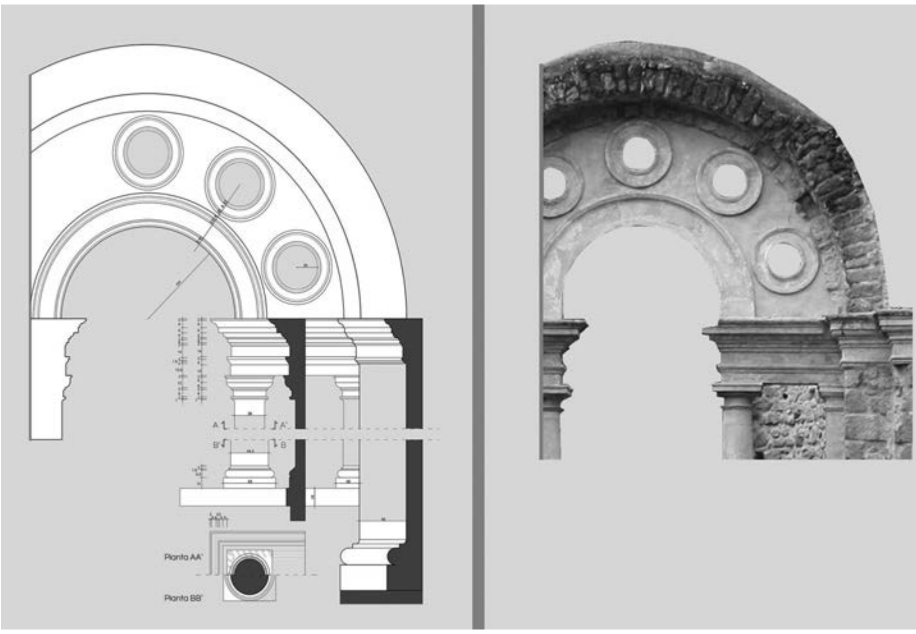

Figure 7. Serliana detail, direct survey and photogrammetry. Author's photos.

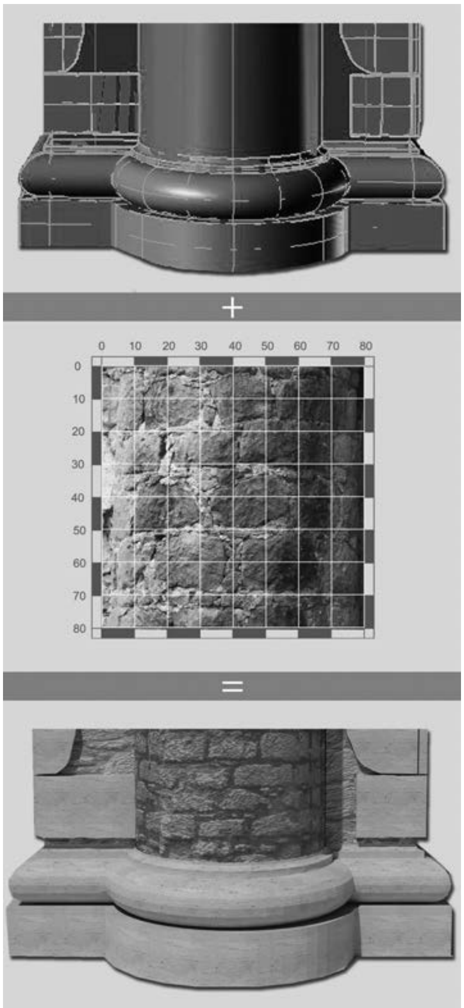

Figure 8. Column modelling, application of materials and rendering. Author's photos.

Figure 9. 3D model and 3D printing reconstruction. Author's photo.

The final phase of the proposed methodology consists of prototyping, i.e. a real, three-dimensional object is printed starting from a virtual, three-dimensional model by a software called MakerBot Replicator. We printed two prototypes: the first describes the current situation, while the second one represents the archaeological and architectural reconstruction of Bramante's project and ideas. The second model is printed in three parts — structure and covers — subsequently assembled together. (Figures 9–14)

Conclusions

This experience demonstrates how Archaeology and Cultural Heritage epitomise the options made available by modern technologies; in the real world and in

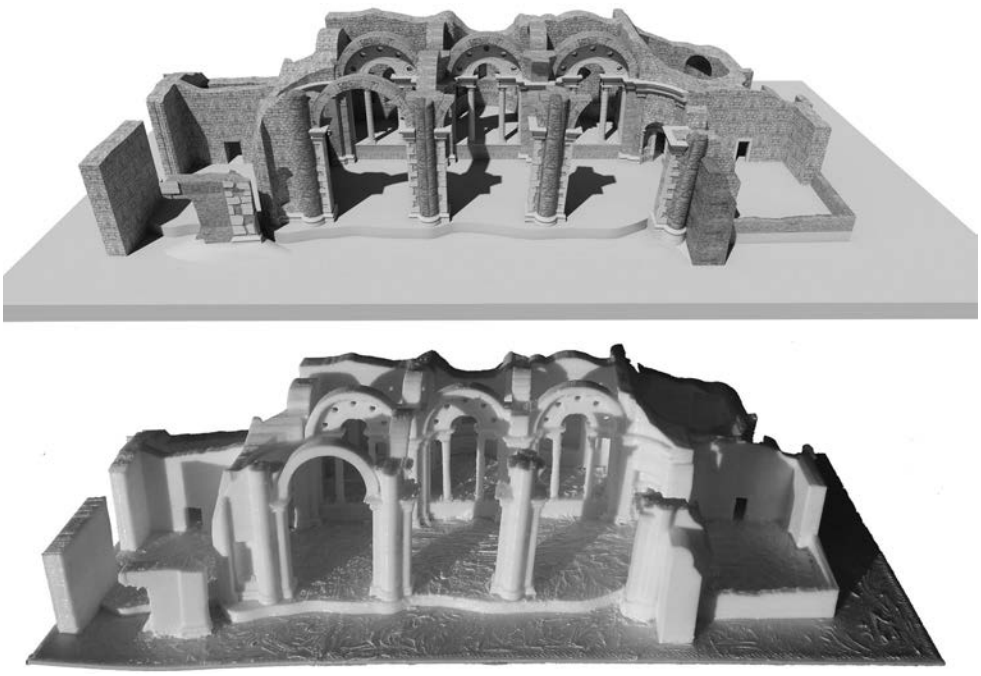

Figure 10. 3D model and 3D printing, current state. Author's photos.

Figure 11. 3D model and 3D printing, current state. Author's photos.

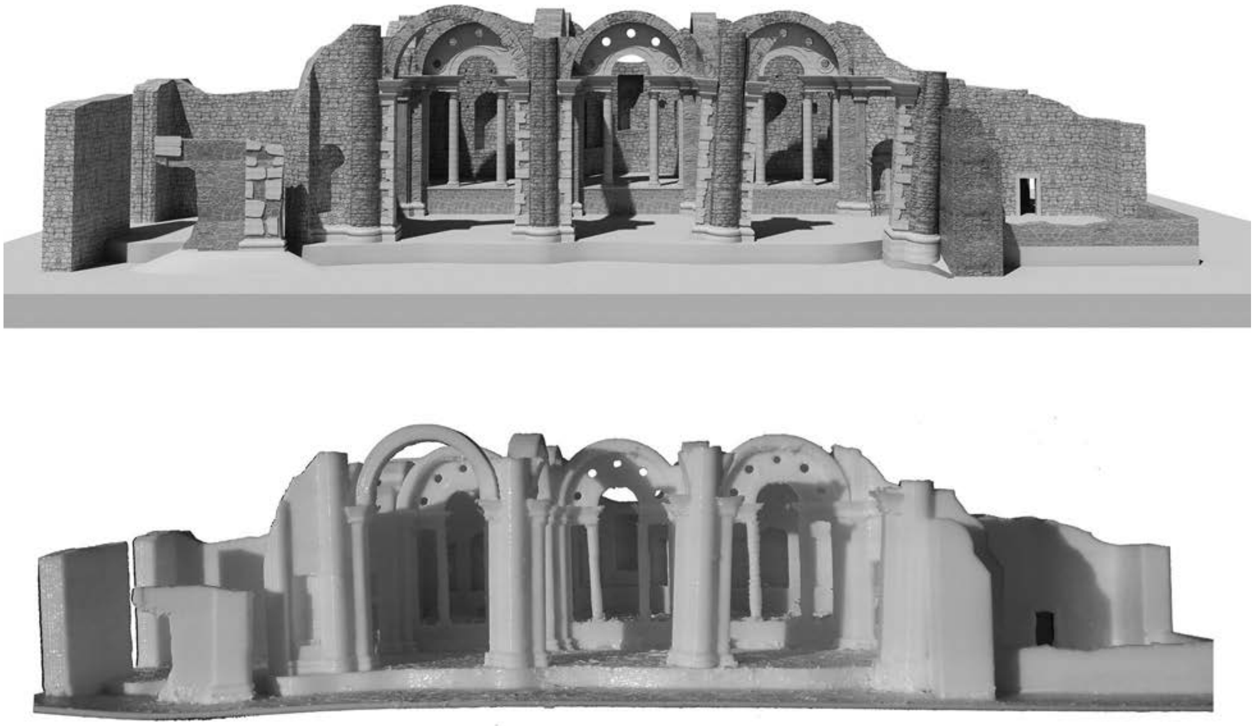

Figure 12. 3D model and 3D printing, current state. Author's photos.

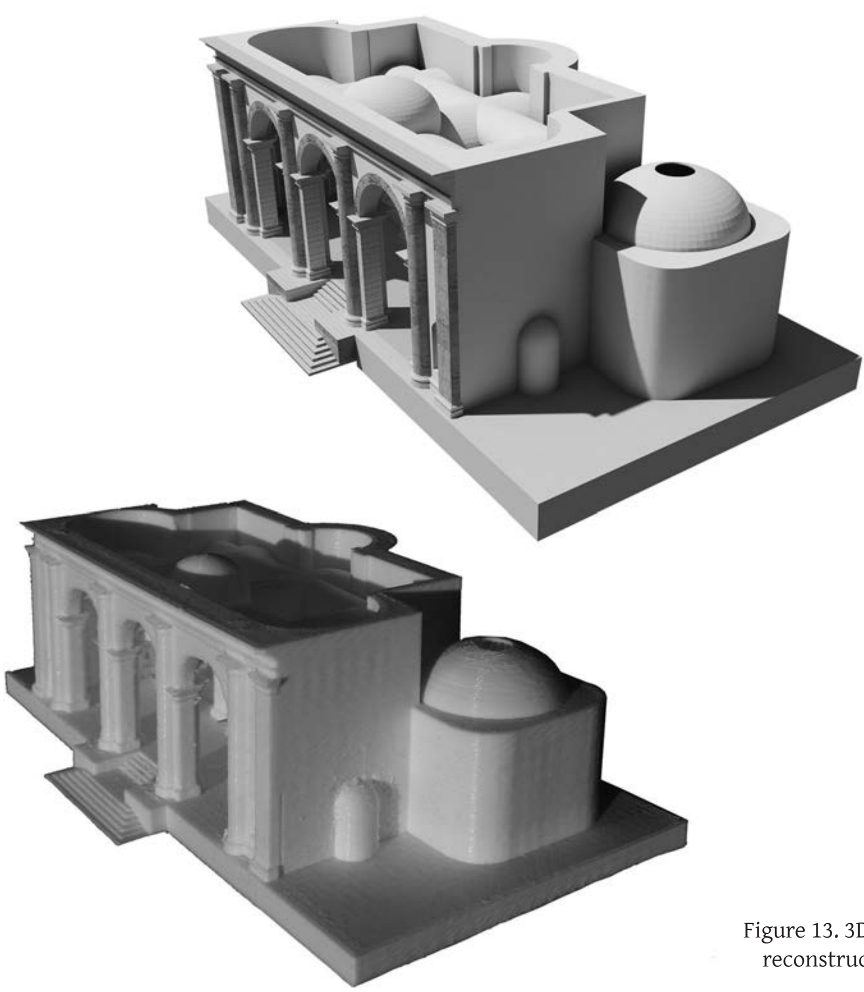

Figure 13. 3D model and 3D printing, reconstruction. Author's photos.

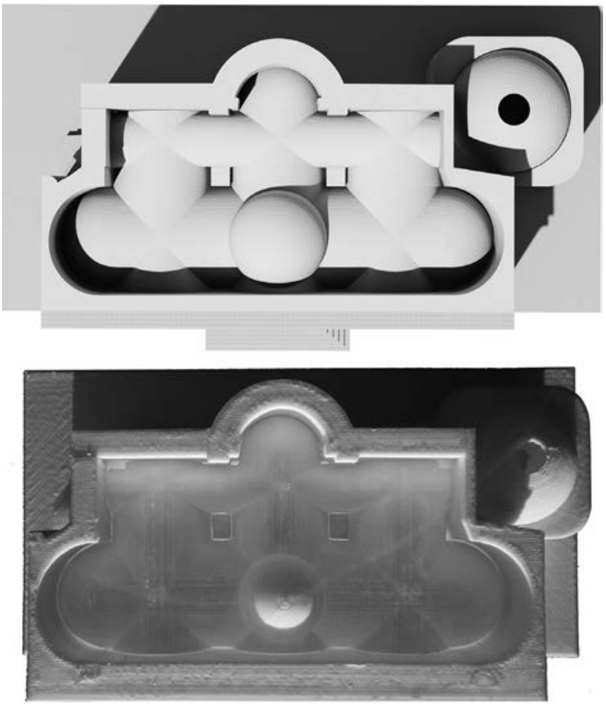

Figure 14. 3D model and 3D printing, reconstruction. Author's photos.

today's society, regardless of the technology used, you must adapt yourself to an operational methodology consistent with the objectives; the latter should incorporate, thanks to the different technologies and interdisciplinary approaches, aspects of survey as well as concepts of dissemination and utilisation. The proposed methodology, thanks to combining data obtained through different techniques into a single reference system, is characterised by an overall geometrical knowledge and faithful reproduction. This allows us to keep interpretive reconstructions separate from the real structure. In addition, three–dimensional models and their subsequent prototypes offer remarkable advantages in other fields, too: for example, to diagnose the degradation of materials or structures, use archive photogrammetry to investigate the transformations that an object has undergone over time, check conservation and maintenance activities, faithfully reconstruct buildings lost or destroyed as a result of war events. Last but not least, this approach can be easily communicated, making research readily accessible and usable. The tactile experience of a work of art takes on special significance (suffice to think of how blind and visually impaired people can benefit from these technologies), hence the empathetic dimension, we believe this is an effective tool for knowledge dissemination: a direct, shared and therefore better perceived tool. It enables research to become tangible.

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Towards a National Infrastructure for Semi-Automatic Mapping of Cultural Heritage in Norway

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Abstract

Airborne Laser Scanning (ALS) is a technique well-suited to creating Digital Terrain Models with the purpose of detecting cultural heritage, given that the cultural heritage manifests itself in the terrain model. This paper presents a pilot web portal for semi-automatic mapping of archaeological features in ALS data. The intended users are archaeologists in the county administrations in Norway. The pilot portal is already a useful tool for archaeologists in the participating pilot counties in Norway, and exposes the need for a national infrastructure for processing of ALS data.

Automatic detection based on deep learning is successfully applied. Traditional pattern recognition methods are also included, but obtain high false positive rates and thus require more manual editing. The web portal supports the following types of cultural heritage: Grave mound, pitfall trap, charcoal burning pit, and charcoal kiln. The web portal is demonstrated with ALS data from three different locations in Norway.

Keywords: Digital Terrain Model, detailed archaeological mapping, Airborne Laser Scanning, deep learning, Norway

Introduction

With the ever increasing pressure on agricultural and forested land for human activities, local municipality authorities are forced to re-think how to manage cultural heritage. The traditional mapping of cultural heritage in Norway was mainly based on chance discovery, and often with inaccurate positioning. Although some accurate and detailed cultural heritage mapping projects have been included recently, the national cultural heritage database is generally perceived as inadequate for planning land use. The development of airborne platforms for the retrieval of optical images has evolved significantly in recent years, and their use has proven helpful in the surveying and conservation of cultural heritage (Wypych *et al.*, 2014). However, optical imaging does not provide enough detail of the ground surface in forested areas and the accuracy of the digital terrain models created from optical data will suffer as a result. Thus, other techniques, such as airborne laser scanning, are a better choice when a detailed mapping of the landscape is required (Chase *et al.*, 2011).

Recently, the Norwegian government decided to finance a new national Digital Terrain Model (DTM) based on Airborne Laser Scanning (ALS) at 2 pulses per below the tree line and automatic image matching above the tree line. This may open the way for semi-automatic mapping of cultural heritage in any region of interest in Norway, provided that the cultural heritage being sought manifests itself in the DTM. However, this calls for the development of a national infrastructure combining the storage and retrieval of ALS data with automatic detection methods.

This work presents an approach towards a national infrastructure by using a web portal developed for use by archaeologists in the county administrations in Norway. The user specifies an area of interest and selects which types of cultural heritage to look for. Since the new national DTM is not implemented yet, the user will need to upload an ALS data set for the area of study. As the processing of large ALS data sets can be time consuming, the user will be notified when the task has been completed by an e-mail, which also contains a link where the processing result in the form of vector files can be downloaded.

Airborne Laser Scanning

ALS is a measurement technique that creates a 3D point cloud model of the landscape, where laser returns from the land being scanned can be separated by standard processing algorithms into two groups of hits, stemming either from the ground or from structures above the ground, including vegetation (Wehr and Lohr, 1999). Ground hits can then be used to create a DTM (Figure 1).

The application of ALS has recently become an additional tool in landscape surveys. This is due to the ability to ‘see’ through gaps in forest canopies, as

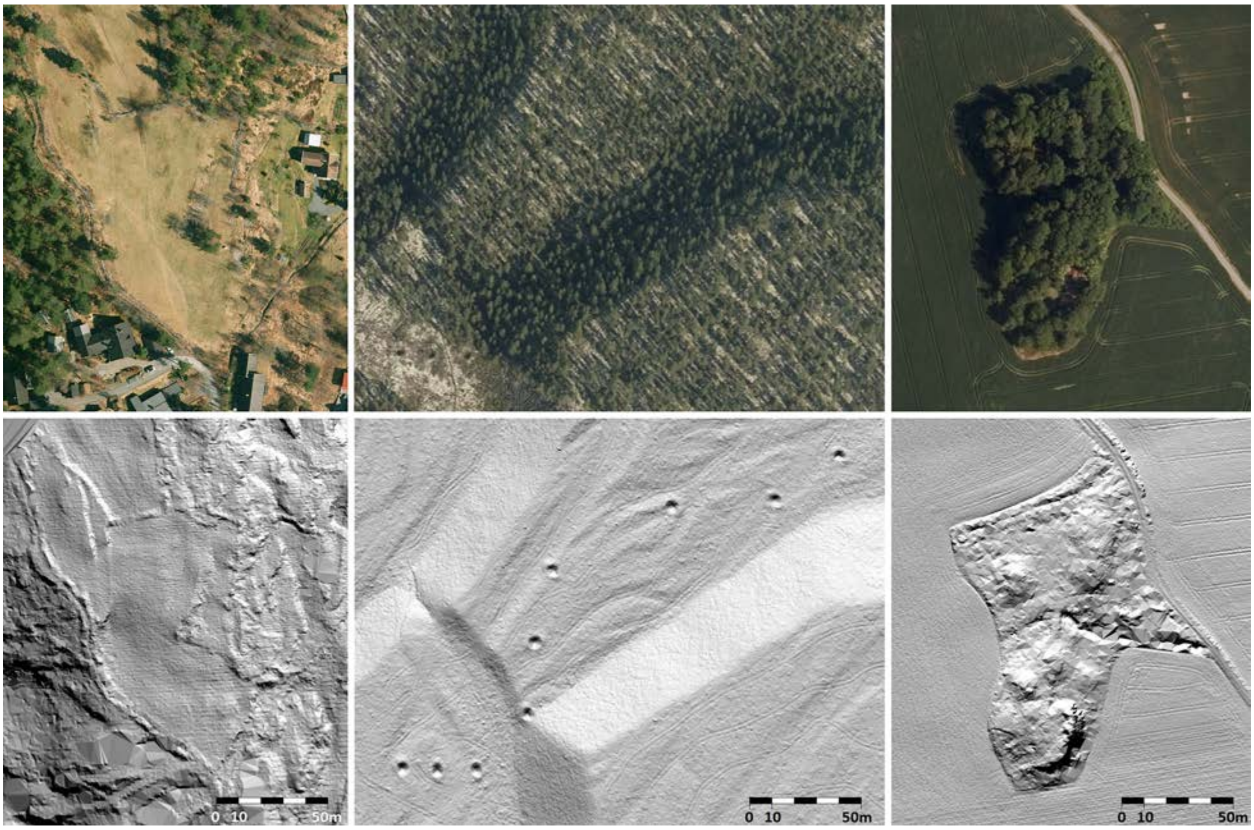

Figure 1. Aerial orthophotos (top row) and DTMs from ALS ground points (bottom row). Left: stone fences at Hovet, Kongsberg municipality, Buskerud County. The stone fences are visible in the orthophoto, but are occasionally hidden by single trees. Middle: pitfall traps from a deer hunting system at Snubblandet, southwest of Lake Olstappen, Nord-Fron municipality, Oppland County. Three pitfall traps, located in a clear cut zone along a power line, are visible in the orthophoto. The other pitfall traps are not visible in the orthophoto as they are hidden by the tree vegetation. Right: grave mounds at Valby, Larvik municipality, Vestfold County. None of the grave mounds are visible in the orthophoto due to the tree vegetation.

well as the cost-efficiency provided by swath mapping from an airborne platform combined with computer processing of data.

Digital terrain models created from ALS ground returns may provide an understanding of past settlements and reveal archaeological artefacts not easily visible in optical images (Figure 1).

A semi-automatic detection approach

By the application of pattern recognition techniques designed for specific archaeological structures, automated searches in the DTM can be made to discover terrain features that are cultural heritage structures (Trier and Pilø, 2012; Trier *et al.*, 2015a, 2018). However, the automatic detection methods are not perfect. Automatic detection of charcoal kilns using deep learning (Trier *et al.*, 2018) resulted in 87% of the true charcoal kilns being correctly identified, meaning that 13% were missed. In addition, 37% of the structures that the automatic method predicted to be charcoal kilns were not (false positives). Thus, an automated search based on such techniques needs to be evaluated through visual interpretation of the ALS data by an archaeologist.

This semi-automated approach by first using an automated method followed by visual interpretation, has been applied in several cultural heritage mapping projects in Norway over the past five years, mapping deer hunting systems, iron production sites, grave mounds and charcoal kilns with promising results (Trier and Pilø, 2012; Trier and Pilø, 2015; Trier *et al.*, 2015a, 2015b, 2018).

Automatic detection methods have also been used for cultural heritage mapping in other countries. Zingman *et al.* (2016) used straight line segment detection for the mapping the ruins of livestock enclosures in optical images of an Alpine region in Switzerland. Schneider *et al.* (2014) used template matching and morphometric variables for the mapping of charcoal kilns in DTMs from ALS data of an area north of Cottbus, Germany. Sevara *et al.* (2016) used the openness visualization method for DTMs for the semi-automatic mapping of individual grave mounds in Sweden's largest Viking Age grave field, located on the Björkö Island in Lake Mälaren.

One of the main obstacles for combining computer–based searching and human-based interpretation is making a system available which exhibits practical usage, and where archaeologists can easily retrieve results from the automated search and quickly review the relevance of detected terrain features. In an attempt to overcome this interface problem, a web-based portal has been developed, as described below.

Deep learning versus traditional pattern recognition

Detection and classification of objects in remote sensing images are often challenging tasks (e.g. see Solberg *et al.*, 2007; Xu *et al.*, 2010; Zhang *et al.*, 2014). This is primarily because it is challenging to design image measurements that are able to capture the visual information needed for robust detection and recognition. Examples of such image measurements include gradients, edge detectors and template matching by image correlation (Gonzalez and Woods, 2008). A common characteristic of the image measurements applied in remote sensing recognition applications is that they are, to a great extent, handcrafted and relatively simple (e.g. Larsen *et al.*, 2013; Brekke and Solberg, 2005). The limited information captured by the handcrafted measurements has often resulted in reduced performance compared to recognition performed by humans.

Krizhevsky *et al.* (2012) demonstrated that convolutional neural networks (CNNs) obtained substantially higher image classification accuracy on the ImageNet Large Visual Recognition Challenge (Russakovsky *et al.*, 2015). Their success was the result of training a large CNN on 1.2 million labelled images, and by using more efficient strategies for training the network. In order to train a CNN with performance metrics comparable to the ones reported by Krizhevsky *et al.* (2012), a large amount of labelled training images are needed. For many applications, the number of labelled training images is too low. However, a combined approach is possible. The image measurements extracted from a deep CNN, carefully trained on the large ImageNet database, may be applied as generic image representations. Then, the last layer in the CNN is replaced by a classifier that is trained on the application-specific images (e.g. see Razavian *et al.*, 2014).

In this project, template matching has been used for automatic detection of circular structures like mounds and pits (Trier *et al.*, 2015a; Trier and Pilø, 2012), while deep learning using a CNN has been used for automatic detection of the more complex charcoal kiln structures.

The CultSearcher web portal

motivated by the need for a semi-automatic tool for detection of cultural heritage, the development of such a system should result in a tool consisting of the following steps:

1. Create a digital terrain model from an available set of ALS data.
2. Search for relevant terrain structures based on the available algorithms and templates to choose from.
3. Present the automated findings with confidence levels both visually as well as in a format that can be used in combination with other software tools.

With these three requirements, a web-portal named CultSearcher has been the implemented using the search algorithms combined with a user friendly

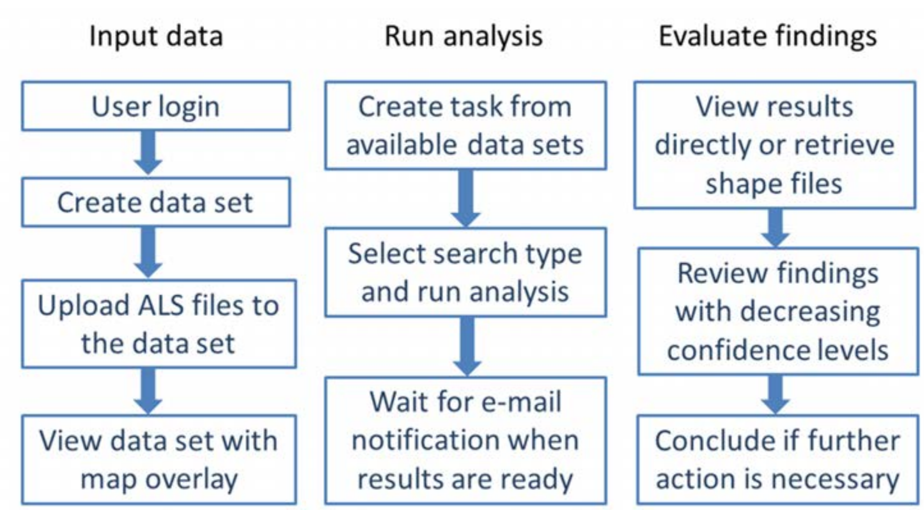

Figure 2. Workflow diagram for the CultSearcher web portal.

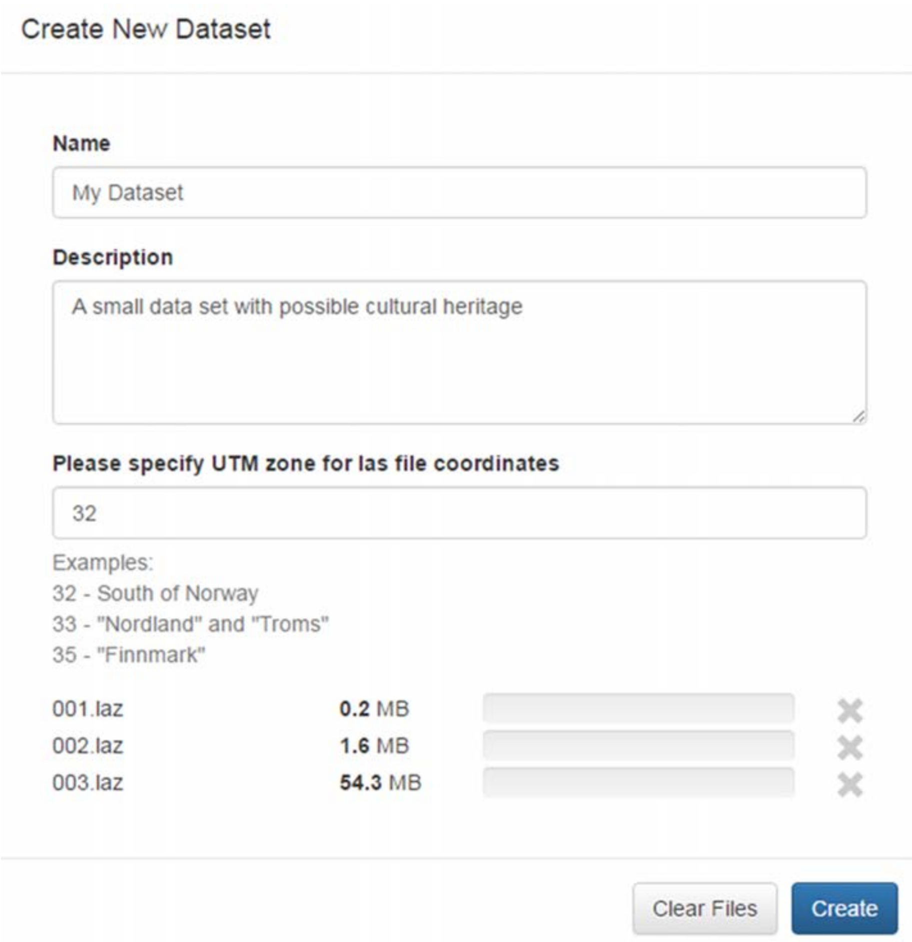

Figure 3. CultSearcher dialogue box for the creation of a new data set and ALS data upload.

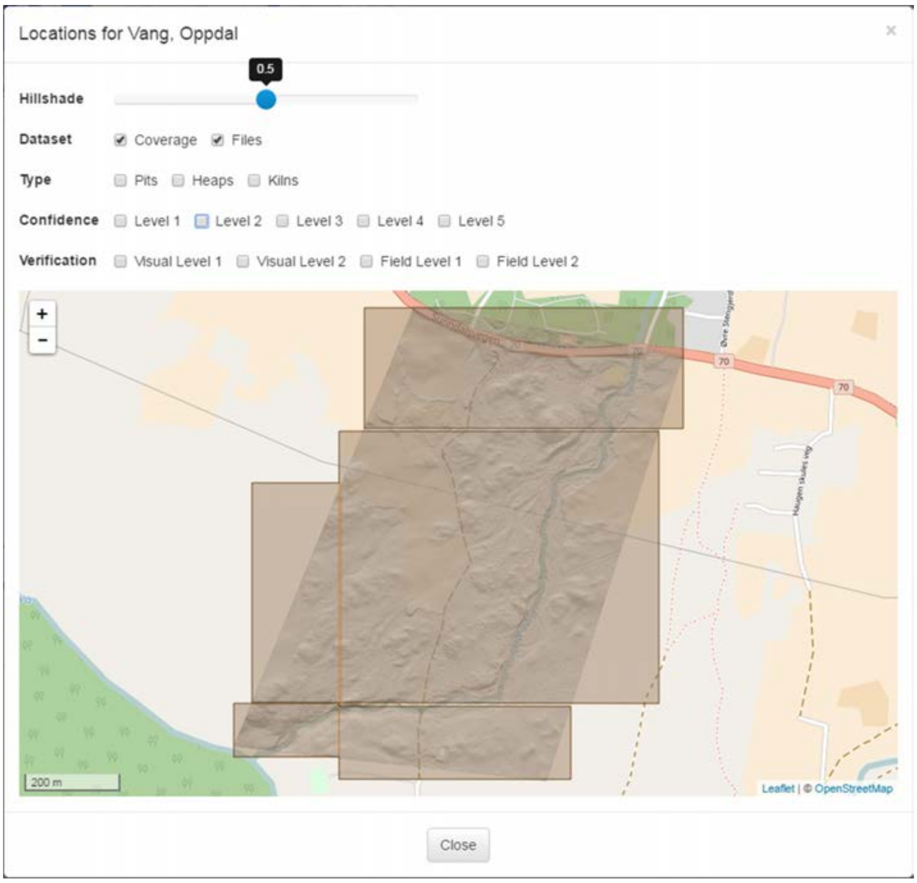

Figure 4. Map of ALS coverage shown as a transparent layer with boxes indicating coverage of each individual ALS file in the data set.

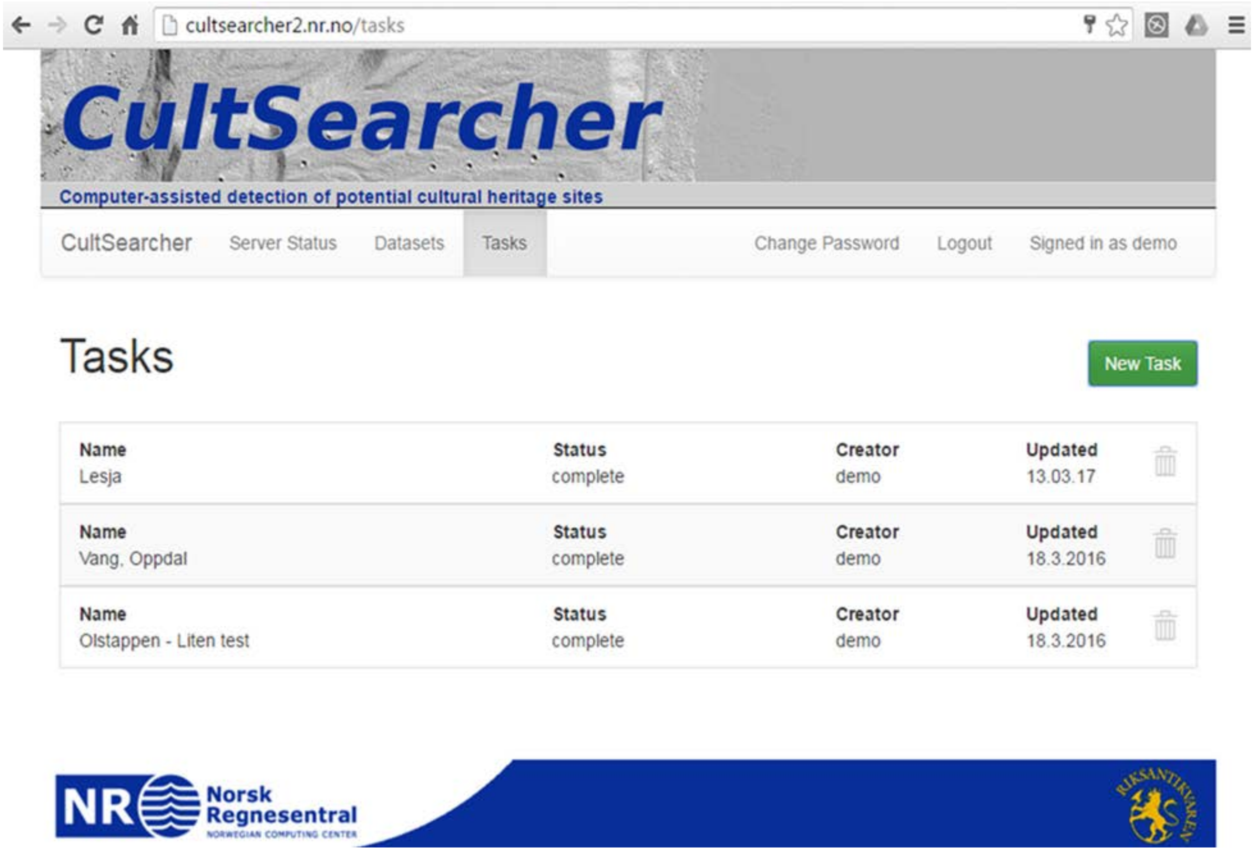

Figure 5. The CultSearcher task pane. Previously run tasks are listed (all are completed). A new task may be defined by clicking the green 'new task' button.

interface, where data may be uploaded, analysed and the results evaluated. The main workflow of the CultSearcher web portal (Figure 2) will be explained in more detail in the next sections.

Input data

After successful login to the CultSearcher portal, the main display presents an overview of available data sets related to the user, and the option to create a new data set by uploading new data, in conjunction with the necessary account administration tasks, such as password change, etc.

To create a new data set, the web portal expects a set of ALS data files and the necessary metadata information required to describe the data (Figure 3). ALS data are usually available as a set of files containing a point cloud with coordinates from the laser returns gathered from the landscape. When the user uploads a set of ALS data files, CultSearcher quickly scans through the header information of each ALS file to retrieve the geographical boundary of the landscape contained in the file. The total area covered by the ALS data set is then combined with a regular map to indicate the locations where data are available, and thus where analysis will be performed. For purposes of visualization, the ALS coverage is displayed as a transparent layer on top of the map (Figure 4).

Run analysis

With a selected data set, a search can be defined through an analysis task. From the CultSearcher task pane (Figure 5), the user may select 'new task', and a dialogue box appears (Figure 6). Specification of the task is done by choosing among the data sets available to the user, what type of searches to perform (pits, heaps or kilns), as well as metadata information needed to identify the task. Currently, the semi-automatic detection of the following types of cultural heritage is supported: grave mound, pitfall trap, charcoal burning pit, and charcoal kiln.

The analysis task consists of three automatic steps:

1. Create a DTM of the ALS ground points in each of the input LAS files.
2. Search for terrain features that are likely to be of the selected type of cultural heritage.

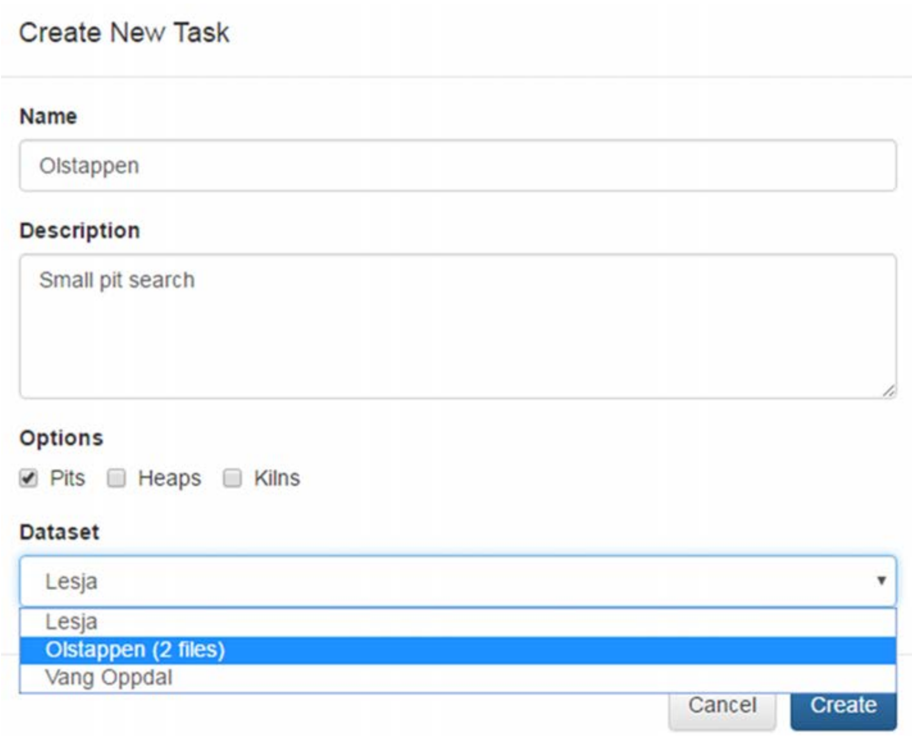

Figure 6. CultSearcher dialogue box for creating a new task. Available data sets are seen in the drop-down list box.

3. Sort the list of terrain features by estimating a confidence level (1–5) for each detected terrain feature.

As the analysis of a large amount of data may be time consuming, an alert is sent by e-mail to the user account as soon as the analysis has been completed. This allows the user to log off and leave the web portal for a later return to review of results from the analysis.

Evaluate findings

When the analysis task has finished successfully, the detection results may immediately be viewed directly in the CultSearcher web portal, or downloaded as a set of vector files for use in other software packages.

The detection results are given in one set of files for each type of cultural heritage specified in the analysis task. Within each type of cultural heritage, the detection results are grouped into five levels of confidence. Detections are marked with circles coloured according to the type of cultural heritage, and the degree of transparency of the circles indicates the level of confidence.

In cases where automatic detection results have already been verified by archaeologists, either by visual inspection of the DTM data or by field inspection, the confirmed archaeological structures may be visualized as a separate layer, which may be toggled on or off. The possibility of combining automatic detections with confirmed findings in different layers is thus a useful tool in the process of verifying the quality of automated detections.

In an area close to Lake Olstappen, in Nord-Fron municipality, Oppland County, a set of detected pits of variable sizes are marked with circles for the three highest levels of confidence (Figure 7). The hillshaded DTM may be displayed on top of a topographic map, by using a slider to adjust the transparency of the DTM (Figure 8). The view may be panned and zoomed easily. This flexibility of usage allows for visual interpretation of the detected terrain features by an experienced archaeologist by toggling the detected terrain features and inspecting the DTM. The detections should be viewed and evaluated successively, starting with the highest confidence level.

Results

Three data sets are shown to demonstrate the capabilities of the CultSearcher web portal. The first ALS dataset covers a 29 km^2 area surrounding the lake Olstappen in Nord-Fron municipality, Oppland County. The ALS pulse density was 10 per m^2, with 7.3 ground hits per square metre on average. This is an area known to contain ancient deer hunting systems, which are composed of pitfall traps and fences. The fences are gone, but the pits remain, albeit slightly eroded. The automatic method was able to detect 96% of the pitfall traps (Trier and Pilø, 2012). On the sedimentary deposits of sand, all pitfall traps were identified by the automatic method, including small ones that had been overlooked by the archaeologists during visual interpretation of

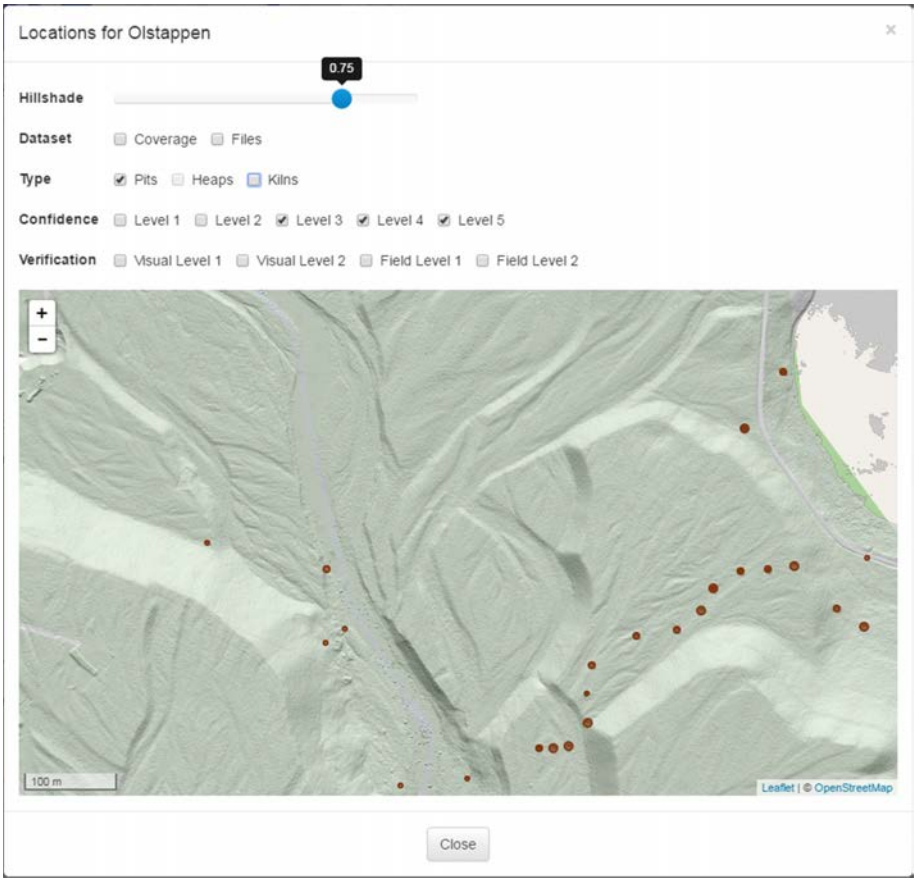

Figure 7. Detection results from a search for pits for the detailed mapping of ancient deer hunting systems. Detected pits are indicated with filled circles. The level of confidence is indicated by varying degree of transparency.

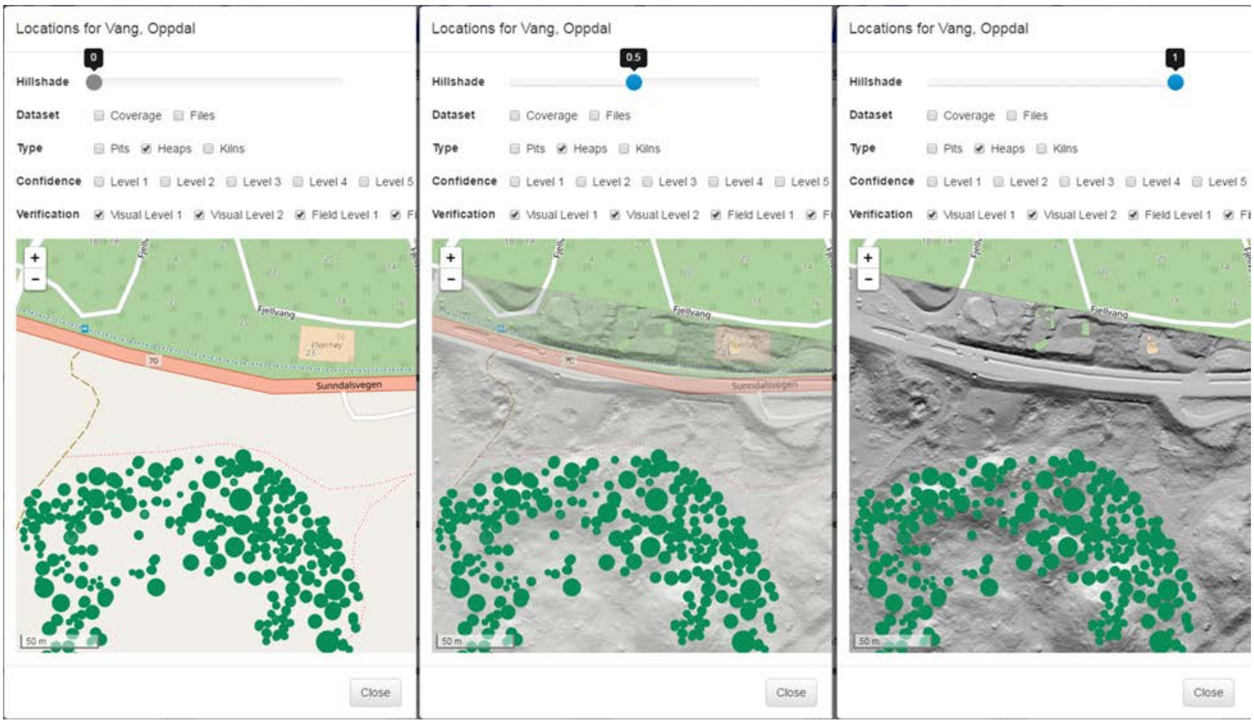

Figure 8. The hillshade slider may be used to adjust the visibility of the hillshaded DTM versus the background topographic map. Left: when the slider is at 0, only the topographic map is visible. Middle: at 0.5, both the topographic map and the DTM are visible simultaneously. Right: when the slider is at 1, the hillshaded DTM blocks the topographic map, which is only visible outside of the area covered by the DTM.

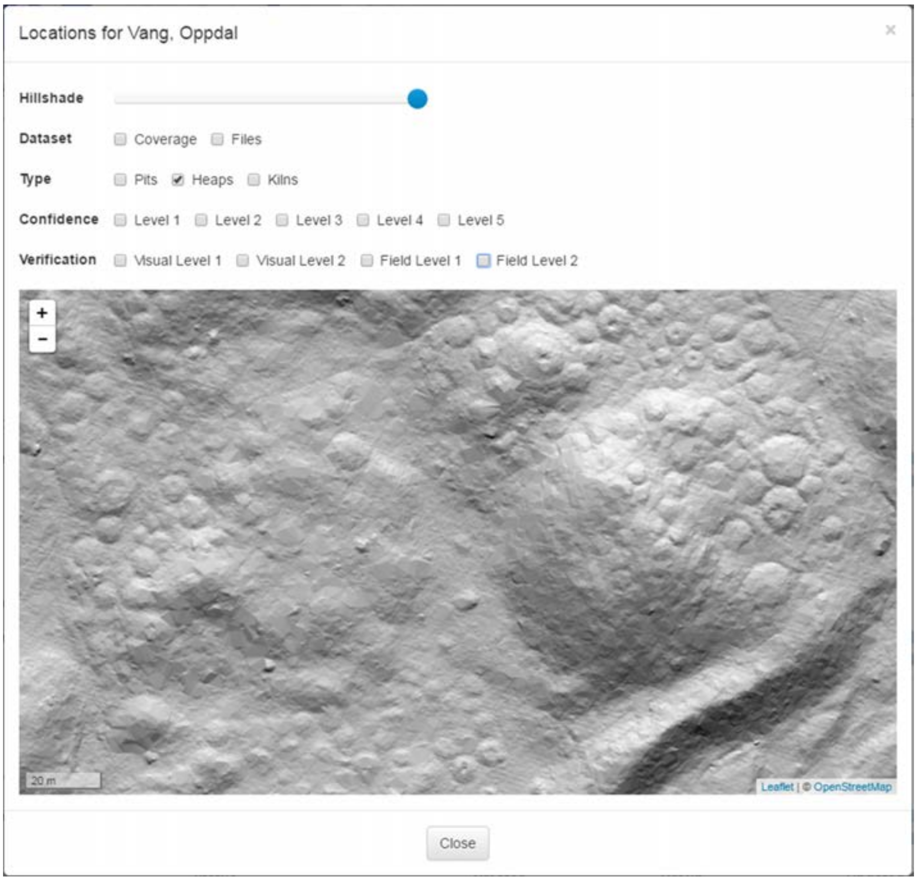

Figure 9. Detail of DTM at Vang municipality, Oppdal County. Several grave mounds are visible.

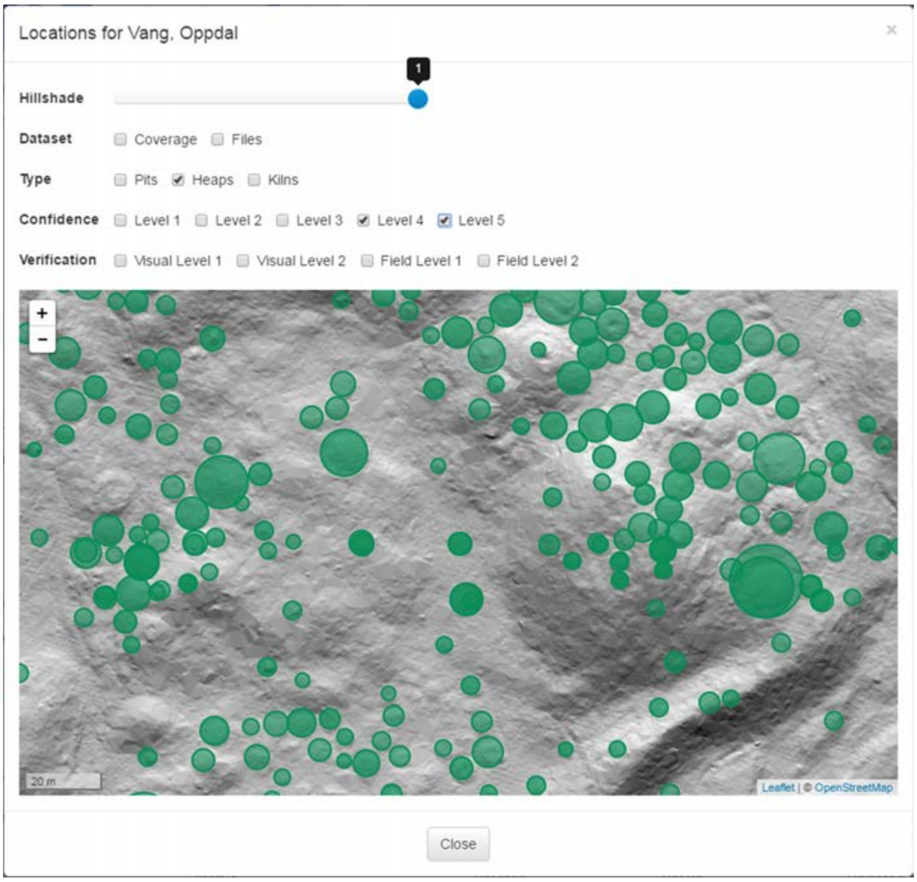

Figure 10. Automatic heap detections of confidence levels 4 and 5 at Vang municipality, Oppdal County.

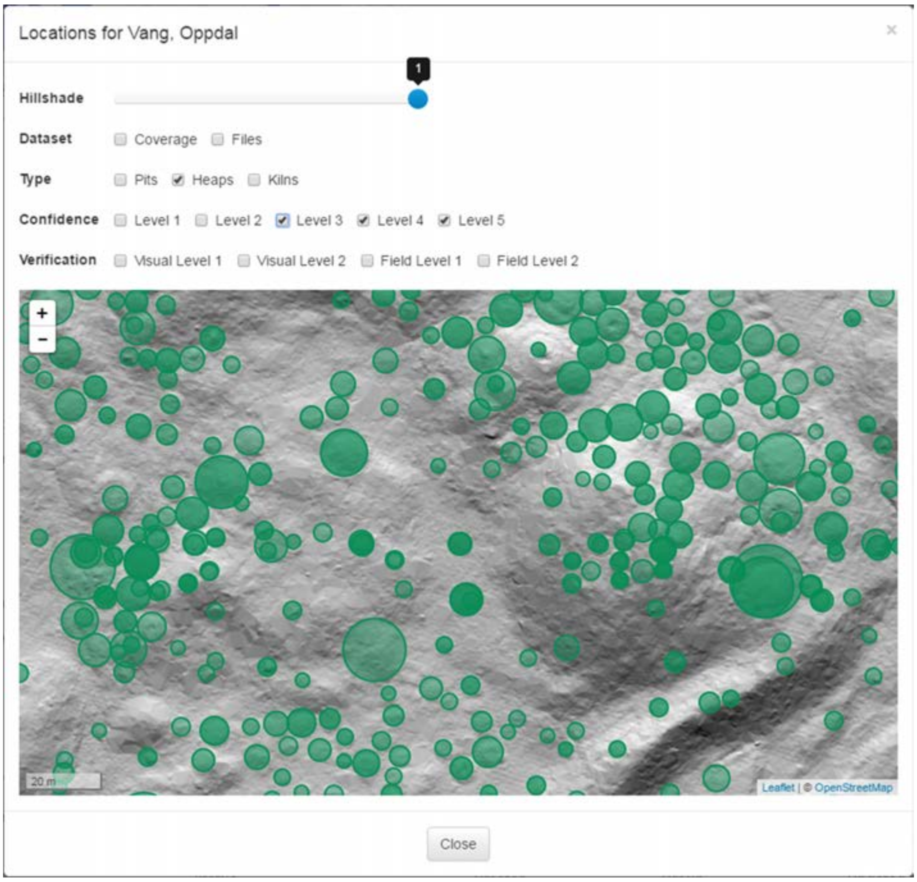

Figure 11. Automatic heap detections of confidence levels 3, 4 and 5 at Vang municipality, Oppdal County.

the DTM. The false positive rate was small in this area. However, in other parts of the terrain, the false positive rate was high. Natural terrain features, like groups of boulders or river courses gave a high response to the pit-shaped template.

The second ALS data set has been recorded in Norway's largest preserved Viking Age grave field at Vang, Oppdal municipality, Sør-Trøndelag County with a specified point density of 12 pulses per m^2. The grave field contains about 1000 grave mounds. The common shape of a mound is circular with a diameter that can vary between 2 and 20 meters. Thus, for automated grave mound detection, the heap search functionality in the CultSearcher web portal is suitable. This data set was described and analysed in a previous study (Trier *et al*., 2015b), and illustrates a search for heaps through template matching, as grave mounds are typically circular in shape and of varying size. Several heaps of variable sizes may easily be seen directly from the digital terrain model created from the ALS data (Figure 9). Many of these are detected at the highest confidence level by the automatic method (Figure 10). However, a number of false positives also appear. As more confidence levels are included from the automatic detection (Figure 11), the number of false positives increases. Still, several true grave mounds are missed (false negatives). To assess false positives, one may turn on verification, field level 2 (Figure 12) and then toggle the automatic detections of, e.g. confidence level 5. To assess false negatives, one may turn on automatic detections of, e.g. confidence levels 3, 4 and 5 (Figure 11) and then toggle verification, field level 2.

The third data set has been recorded in Lesja municipality, Oppland County, and demonstrates the CultSearcher portal's capability for kiln searches. The ALS data was collected with a specified point density of 5 pulses per m^2. This study uses deep learning in place of template matching, and results in improved detection performance in terms of lower false positive and false negative rates (Trier *et al*., 2018).

Based on the discovery of iron ore in the Lesja area, an Iron Works was established in 1660. The Iron Works required charcoal, which rapidly led to the establishment of a large number of charcoal kilns in the surrounding forested area. A kiln is circular in shape, and is often surrounded by a ditch or smaller pits — sometimes both. Such a pattern is more complex than a single geometric shape, which is the case for pit-fall traps and grave mounds, and is thus more difficult to detect through template matching. For this reason, a deep learning algorithm (Trier *et al.,* 2018) was used.

For the Lesja data set (Figure 13), validated charcoal kilns from field work is also available. The validated charcoal kilns may be displayed as a separate layer

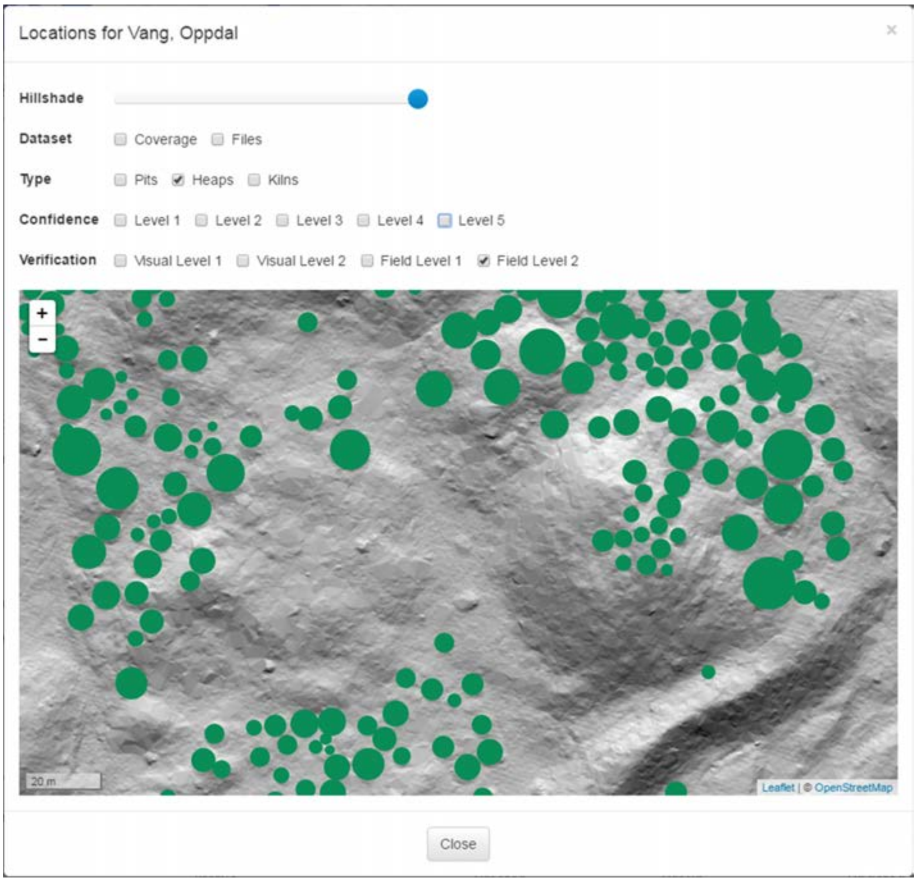

Figure 12. Grave mounds confirmed by field inspection at Vang municipality, Oppdal County.

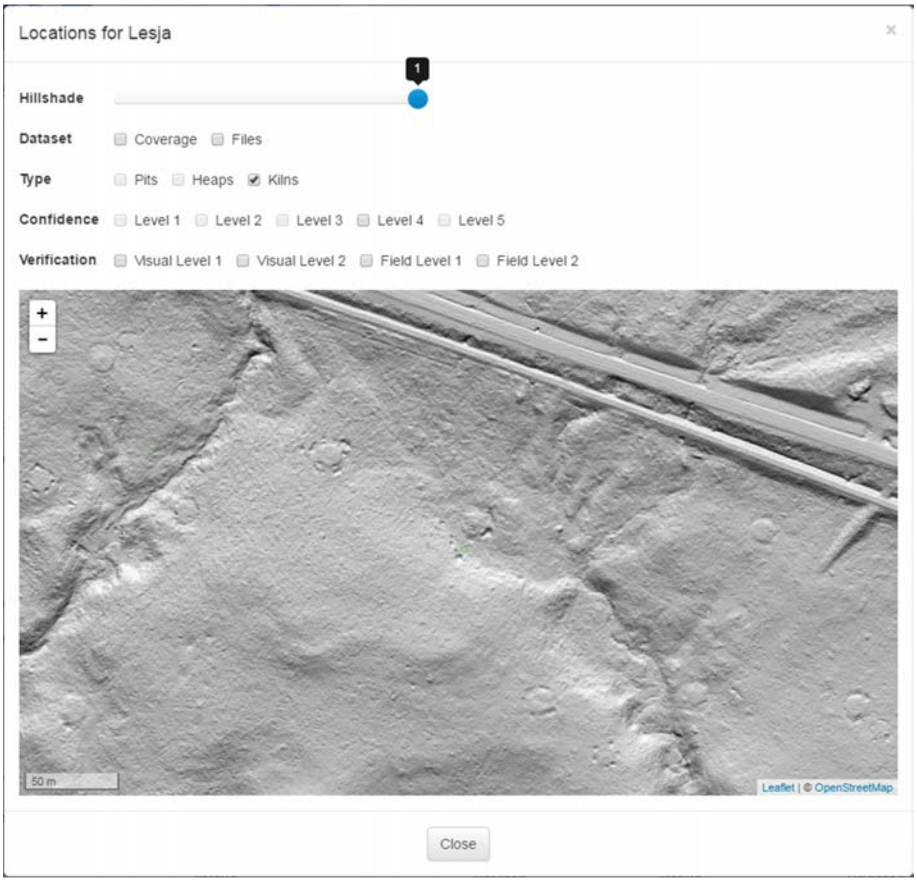

Figure 13. A small part of the digital terrain model obtained from ALS data acquired for the entire Lesja valley.

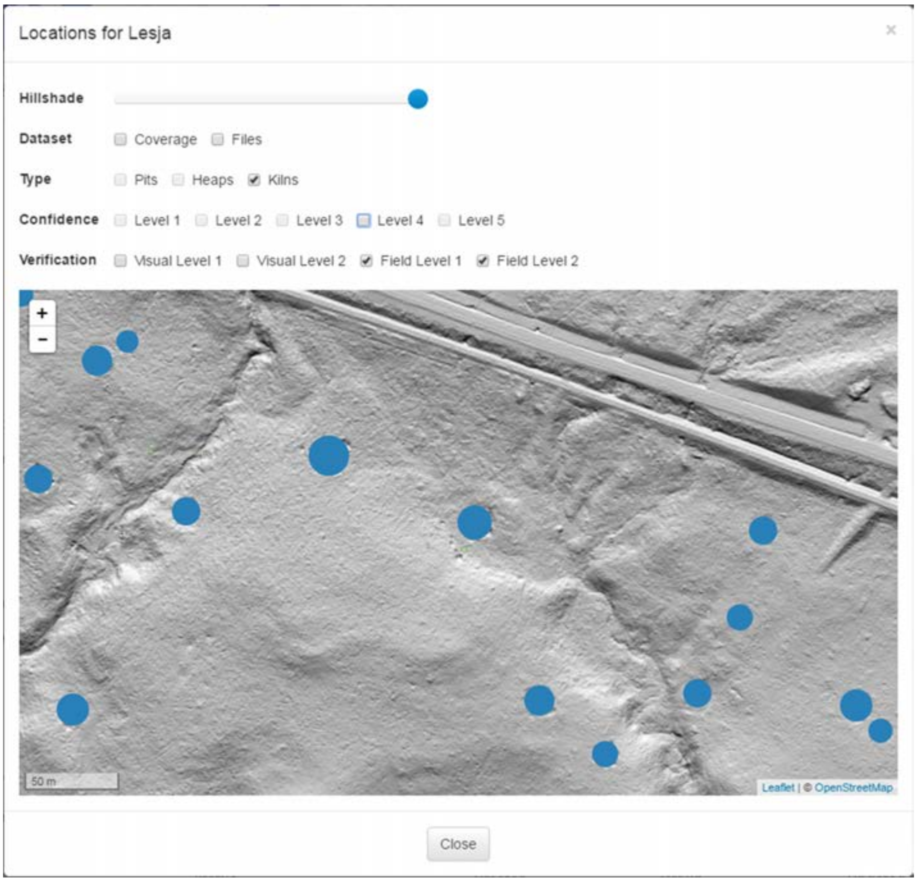

Figure 14. Charcoal kilns verified by visual inspection of the DTM followed by field inspection.

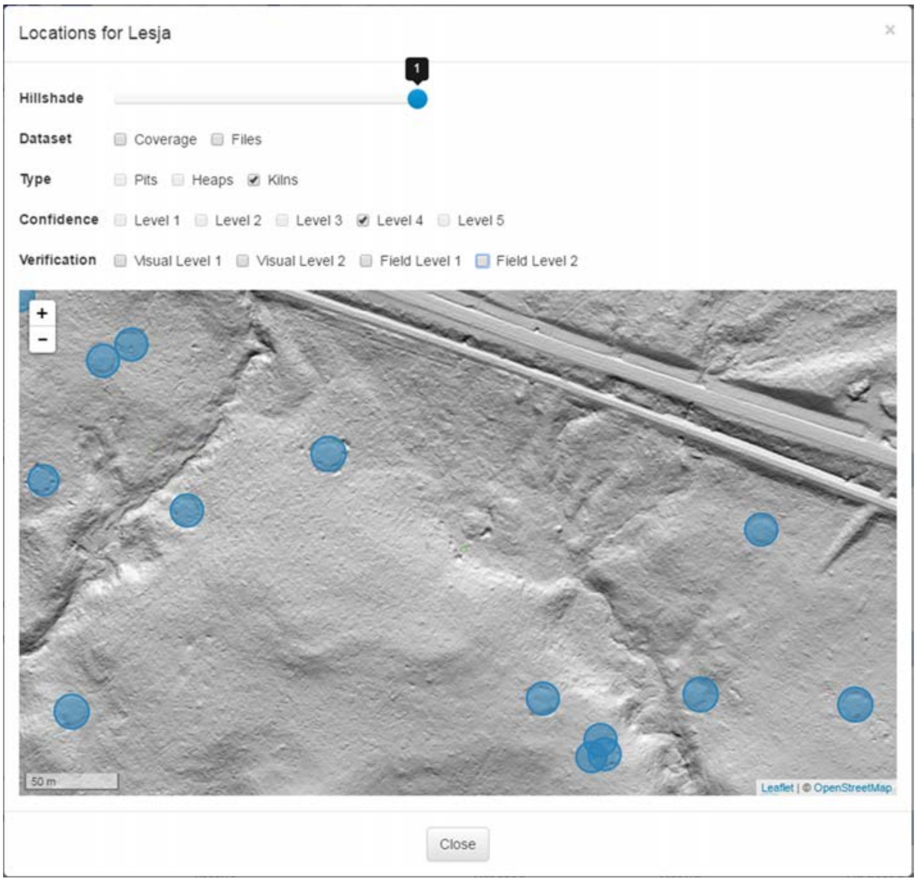

Figure 15. Result of automatic kiln detection (transparent circles) for the area in Figure 13.

(Figure 14) and compared directly with automatic detections (Figure 15).

Discussion

Since the automatic methods do make mistakes, one may question whether they have any value at all. They tend to work best for the archaeological structures that are easily identified manually in the DTMs. However, from practical use by archaeologists in several cultural heritage mapping projects, the feedback we receive is that imperfect automatic classification is better than no classification as an aid in visual interpretation and for selecting areas for field verification. The automatic classification results have improved the completeness of the subsequent manual interpretation. Several true archaeological structures that the archaeologists would have otherwise overlooked have been identified by the automatic methods (Trier and Pilø, 2012; Trier *et al*., 2015a, 2015b). However, there may still be archaeological structures that have been overlooked by both the automatic methods and the archaeologists.

An automatic method is only able to detect structures that are similar to the ones that it has been trained to look for, and may not work in landscape types that are different from the ones found in the training data. The landscape type may reduce detection performance in two ways. First, the landscape type influences to what extent the archaeological structures stand out well from natural terrain structures, thus lowering the detection rate, i.e. increasing the false negative rate. Second, the landscape type influences to what extent natural terrain features are mistaken as archaeological structures, i.e. the false positive rate increases.

If one already has an automatic method for one type of archaeological structure, and wants to use it in a new type of terrain, then one strategy could be to apply it on a representative but limited part of the terrain, and then to manually correct the classification result and include it in the training data. If, however, a different type of structure is to be mapped, then one needs to start by manually labelling examples of the desired structure. With a pre-trained deep convolutional neural network, like the one used for the mapping of charcoal kilns in Lesja (Trier *et al*., 2018), a few hundred examples are needed.

The successfulness of using automatic detection methods as a tool in detailed archaeological mapping is dependent on the following:

1. The existence of data in which the archaeological features of interest are apparent.
2. The existence of automatic methods for the detection of each of the relevant types of structure
3. That the false positive and false negative rates are reasonably low.
4. That the processing time is within reasonable limits.

The national new Digital Terrain Model (DTM) project in Norway will ensure that all forested land will be covered by ALS data with at least two first returns per m^2. This may or may not be sufficient for archaeological mapping, depending on the density of the forest canopy cover and the sizes and shapes of the archaeological structures. For the detailed mapping of grave mounds in forested areas, we have experienced that the automatic detection methods are able to detect the grave mounds, albeit with a high false positives rate (Trier *et al*., 2015b). However, visual interpretation is difficult, since small details of each grave mound are lost. This includes a shallow ditch that may appear along the circumference, and a small pit on the top that may be present due to looting or the collapse of structures inside the mound. With higher density ALS data (at least 5 first returns per m^2), these details are better preserved. For this reason, it may be necessary to acquire ALS data at higher density for areas that need detailed archaeological mapping. However, the emitted laser pulse density is not the only factor that affects the visibility of archaeological structures in the DTM. Dense forest limits the ability of the laser beams to hit the ground and return to the sensor, thus reducing the density of ALS points on the ground surface. The sizes and shapes of the archaeological structures are also relevant. Large structures require lower ALS ground point density than smaller structures, while structures with a lot of detail (e.g. narrow/shallow ditches around charcoal kilns) require higher density than equally large structures with little detail.

For a limited area with a high density of cultural heritage structures, as the Viking Age grave field at Vang, the number of false positives is naturally limited by the amount of free space between cultural heritage structures in the landscape. On the other hand, if the method is to be applied on large areas where the expected density of cultural heritage structures is low, then the false positive rate must also be low for the method to be perceived as useful. When applying the template matching method on the entire Larvik municipality, Vestfold County, Norway (Trier *et al*., 2015a), the false positive rate was high.

The use of deep learning to detect charcoal kilns (Trier *et al*., 2018) demonstrated that reasonably low false positive and false negative rates are indeed feasible. We recommend that an approach including deep learning algorithms should also be used for the detailed mapping of grave mounds, hunting systems, iron extraction sites, stone fences, hollow ways, etc. Previous attempts in Norway based on traditional pattern recognition have, at best, been limited to terrain types in which the archaeological features stand out very well (Trier and Pilø, 2012). In other terrain types, these methods have been less successful, due to a large number of false positives (Trier *et al*., 2015b).

We recommend that deep learning be used for the detailed mapping of all archaeological structures that are automatically protected by Norwegian law. 18th century charcoal kilns are not automatically protected; however, grave mounds are, and they exist in all of Norway's 19 counties.

Deep learning requires a few hundred training examples of each type of archaeological feature to be detected. We already have more than 1000 grave mounds located in ALS data sets from Vestfold and Sør-Trøndelag counties. Therefore, making an automatic detection method for grave mounds, based on deep learning, seems feasible.

With huge amounts of DTM data, processing time is an important factor to take into consideration, as Norway's total land area is 324,000 km^2. The deep convolutional network, which is used in the deep learning approach, is implemented on a graphics processing unit (GPU), which costs about EUR 500. Processing of 9 km^2 for the charcoal kiln detection experiment (Trier *et al*., 2018) required 24 hours. However, huge reductions in processing time are possible. Instead of extracting 20 m × 20 m image portions in a sliding window approach, then rescaling each image to increase local contrast, the entire image could be pre-processed to obtain a local relief image by subtracting a smoothed version of the DTM. Processing time may be further reduced by running on several GPUs in parallel.

In lack of a national infrastructure for ALS data and the upcoming detailed DTM, the current web portal is based on ALS data uploading by each individual user. After the bulky data transfer, the processing may start. However, in a national DTM infrastructure, no data upload would be needed. Processing capacity may be fully utilised by running the automatic detection methods on a queue of DTM data. Archaeologists in the county administrations would need a user interface to check if their areas of interest are already processed or if they need to request high priority in the processing queue. In the latter case, they would probably require an expected delivery date and a notice when the detection results are ready for visual inspection and correction. Only after editing by archaeologists should the cultural heritage mapping be made available for land use planning.

The archaeologist may want to do one or more of the following:

1. View automatically detected terrain features.
2. Confirm (or reject) individual terrain features by visual inspection of the DTM data.
3. Lock a small area for field inspection, to prevent duplication of field work. Complete by confirming and rejecting a number of individual terrain features.
4. View confirmed and rejected terrain features to correct mistakes.

This implies that any terrain feature may have a history of states, e.g.:

A. Automatic detection as charcoal kiln. Confirmed by visual inspection. Confirmed by field visit.
B. No automatic detection. Added by visual inspection. Rejected by field visit.
C. Automatic detection as pitfall trap. Confirmed by visual inspection, Changed to charcoal burning pit by field inspection.

Each state needs a time stamp and field of metadata containing information about which person or what automatic process made the change.

If the geographic area of interest is covered by more than one data acquisition project, then the borders must be shown clearly.

Conclusions

A pilot of a user-friendly web portal for semi-automatic detection of cultural heritage structures based on data from airborne laser scanning has been demonstrated. The web portal provides an infrastructure that can handle large data sets and is already a useful tool for archaeologists in the participating pilot counties in Norway, and demonstrates the need for a national infrastructure for processing of ALS data.

Future work will include data sharing among users, improved detection algorithms using deep learning algorithms and an improved system for interactive use by archaeologists.

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Experiments in the Automatic Detection of Archaeological Features in Remotely Sensed Data from Great Plains Villages, USA

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Abstract

A variety of remotely sensed data sets have been obtained at numerous archaeological villages in the Northern Great Plains, USA. Manual interpretation of large data volumes requires great effort and cost for trained personnel because village sites typically contain thousands of archaeological features. In the Plains, and indeed throughout the world, countless village sites remain to be explored which makes it worthwhile to examine automated means for archaeological feature identification. Magnetic gradiometry and high resolution DEM data from mid-fifteenth century Huff village, in North Dakota, are examined. Relatively simple GIS reclassification operations combined with indices of shape and size are generally employed, but local texture measures and template-matching are also utilised. These tools permit automatic extraction of fortification ditches, bastions, houses, ceremonial structures, plazas, borrow pits, hearths, and more than a thousand corn storage pits, suggesting great promise for future work of this kind in the Great Plains.

Keywords: automatic feature extraction, remote sensing, Great Plains villages

Introduction

Remote sensing methods have been applied at nearly a dozen village sites along the Missouri River in North and South Dakota over the past two decades. All have been investigated with ground-based geophysical methods, including magnetic gradiometry, electrical resistivity, electromagnetic induction, and ground-penetrating radar (see Kvamme, 2003, 2007). High resolution Digital Elevation Models (DEM) have been generated for many of them by systematic robotic total station surveys with half-meter or less point spacing (Kvamme *et al*., 2006) or acquired through LiDAR surveys at even higher spatial resolutions. Colour and thermal infrared aerial imagery has also been obtained at several of these sites (Hailey, 2005; Kvamme and Ahler, 2007).

Many of these villages are prehistoric, dating as early as the thirteenth century, but others were occupied into the historic period up to the mid-nineteenth century. Most are ancestral to a farming tribe known as the Mandan. These sites range in size from 1–12 ha, are fortified with deep ditches once associated with palisades, and defensive bastions tend to occur at regular intervals. One side of each village is sited adjacent to the steep escarpment that typically borders the Missouri River, which was also defensive. Houses are often distributed irregularly within villages, but in some they are organised in long rows separated by something akin to lanes. A centrally placed plaza for tribal gatherings and ceremonies is devoid of constructions. In early periods (relevant here) houses were approximately rectangular (about 7 × 16 m, slightly wider in the rear) with gabled roofs that may have been covered with bison hides lying atop wooden support beams. The long axis of earthen walls was oriented northeast-southwest with principal hearths located along centre-lines. Entryways were linear, projecting to the south-west. Later structures known from historical illustrations were hemispherical, entirely earth-covered, and are well-described as ‘earthlodges’. A single structure much larger than the others was used for ceremonial purposes and always placed adjacent to the plaza. Corn storage pits 1.5–2 m deep and bell-shaped in cross-section were ubiquitous throughout the villages, including house interiors (Mitchell, 2013).

An advantage of doing remote sensing in the Northern Great Plains is the relative ease by which the sources of anomalies may be identified. Many houses, fortification ditches, and bastions may still be discerned as subtle depressions in the present-day ground surface and, indeed, the high resolution DEM forms a major prospecting tool when subjected to various visual enhancements (Bennett *et al*., 2012). Sources of smaller anomalies may be identified through use of manual one-inch diameter (2.54 cm) soil coring tools, which are easily punched into the common silt-loam to depths exceeding two meters. Careful inspection of extracted sediments, which includes depth measurements, permits identification of such features as hearths and corn (maize) storage pits hidden beneath the surface and commonly revealed only by magnetometry. Decades of experience with such forms of validation (including extensive validations in the case study site below) now make interpretation of remote sensing results much easier and more reliable. A suite of archaeological features that commonly occur in Northern Plains villages can be consistently identified through examination of multiple remotely sensed data sources. They are summarized in Table 1 along with the principle data sets by which they are typically identified.

Archaeological Feature	Commonly revealed by:
Fortification ditches	MG, RES, DEM[1], AIR, TIR, less reliably: GPR
Bastions	MG, RES, DEM[1], AIR, TIR, less reliably: GPR
Plazas[2]	MG, RES, GPR DEM, AIR, TIR
Houses	RES, DEM[1], AIR, TIR, less reliably: MG, GPR
Ceremonial house	RES, DEM[1], AIR, TIR, less reliably: MG, GPR
Earth borrowing pits	RES, DEM[1], AIR, TIR, less reliably: MG[3], GPR
Hearths	MG, less reliably: GPR
Corn storage pits	MG, less reliably: GPR

[1]When topographic variation present in shallow site
[2]Plaza revealed by absence of anomalous indications
[3]A hearth must be absent to distinguish from houses, confirmed by MG

Table 1. Archaeological features in Plains villages commonly revealed through various forms of archaeological remote sensing, including ground-based geophysics. KEY: AIR=aerial/space imagery (vegetation marks), DEM=digital elevation model, GPR=ground-penetrating radar, MG=magnetic gradiometry, RES=electrical resistivity; TIR=thermal infrared.

Problem statement

Despite these foregoing advantages, the problem remains that interpretations of remotely sensed data require a great amount of time and effort for trained personnel to undertake. Moreover, even a moderately sized village may contain 50–100 houses, even more hearths, and thousands of corn storage pits. Hundreds of villages are known to exist and most remain to be explored in the future (Johnson, 2007). Vast remotely sensed data sets, whether from LiDAR, air or space imagery, or ground-based geophysical surveys are being acquired at an ever increasing rate. It is therefore worthwhile to explore automated means for archaeological feature identification from remotely sensed data.

A small amount of work has been undertaken in the automation of archaeological feature detection in satellite, aerial, and LiDAR data. An early approach by Lemmens *et al.* (1993) was moderately successful in identifying circular crop marks in aerial imagery by detecting abrupt brightness transitions at the same radius around any given locus. Bescoby (2006) investigated radon transformations that were capable of extracting linear features from aerial imagery. Space scientists often employ a template-matching approach (described in detail below) for identifying craters on planetary bodies, and many variations to the basic algorithm exist for recognizing various shapes (Kim *et al.*, 2005). Recently, these approaches have begun to appear in archaeological remote sensing as a means for feature detection. Trier *et al.* (2009) identified circular mounds in Ikonos satellite imagery from Norway and Kvamme (2013) employed an identical approach to recognize circular ring structures in aerial imagery from the Great Plains, USA. Similar template matching has also been applied to high-resolution LiDAR to identify archaeological pit features (Trier and Pilø, 2012). In the following, template-matching and far simpler tools available within most GIS are examined as an initial exercise for archaeological feature recognition in Great Plains villages.

A difficulty often exists in conveying the relevance and potential importance of this kind of research. On the one hand there is resistance to the idea that computer algorithms or 'machine intelligence' might come to replace human interpreters (e.g. Parcak, 2009, p. 111). On the other, there is a fundamental misunderstanding behind reasons for this area of investigation. A common observation, for example, is that a human observer can easily recognise many of the archaeological elements listed in Table 1, so why invest in complex computer operations that attempt to do so — especially when their accuracy may be less than that of a human observer? Of course a trained observer may generally define archaeological features easily, rapidly and with greater accuracy than computer algorithms in many contexts at present. This is certainly true in the case study of the single site presented below. However, the point is that with recent advances in remote sensing technology, where large swaths of the earth are imaged in high detail and with great frequency, we need automated mechanisms for the detection and definition of archaeological features as a means to locate, inventory, and ultimately manage heritage resources. Perhaps such methods may ultimately best serve as devices for image pre-screening, where potential archaeological features might be flagged for later review by trained observers. Whatever the case, it is hoped the tools advocated in this paper represent a small step toward this goal.

Data

A case study is employed in this investigation based on an archaeologically well-known village named Huff, which dates to the mid-fifteenth century and forms a state park in southern North Dakota. The site contains long rows of uniformly spaced houses that are primarily rectangular in shape surrounding a centrally located plaza with a large ceremonial house adjacent to it. The village is rectangular in shape, nearly 5 ha in area, and is surrounded on three sides by a fortification ditch and uniformly spaced bastions, with the fourth (eastern) side adjacent to the Missouri River. The village represents a relatively short occupation of perhaps a generation, with major archaeological excavations described by Wood (1967).

Only two site-wide data sets are available for this village: a DEM generated by robotic total station and magnetic gradiometry (Figure 1a, b). The latter was acquired with a Bartington 601 dual fluxgate gradiometer with 0.1 nT resolution, eight measurements per linear meter acquired in transects separated by a half-meter (for 16 measurement/m^2). The primary data for the DEM was obtained by robotic total station (Kvamme *et al*., 2006) with sub-centimetre accuracy and an average point spacing of 0.35 m; these data were interpolated by the inverse distance-weighting algorithm to form a DEM in raster format with 0.25 m spatial resolution. While additional data sets (Table 1) would be useful, such as electrical resistivity which clearly defines house floors in the limited area of the site examined (Kvamme, 2007, p. 214), imbedded within the DEM lies information about house locations, their sizes, shapes, and orientations, as well as the defensive ditch, bastions, borrow pits and the central plaza. The magnetic gradiometry data holds information potentially pointing to the locations of hearths (by thermoremanence), and storage pits tend to be highly recognisable because when they were abandoned their large volumes were filled with magnetically enriched settlement soils that generate pronounced induced anomalies (Kvamme, 2007).

In addition, a great amount of spatial patterning aids this quest. Hearths associated with houses always occur centrally and on their long-axis centrelines. Storage pits are distributed according to three spatial patterns: (1) along the inside perimeter of fortification ditches, (2) along the outside perimeter of houses, and (3) along the inside perimeter of houses. Thus, most of the archaeological features detectable by remote sensing in Northern Plains villages (Table 1) may be defined by these two data sets and their spatial arrangements alone, provided that the data are of sufficient quality to reveal the archaeological features of interest.

Pre-processing

All of the data were imported to GIS as raster data sets. Pre-processing of the data is useful for eliminating unwanted trends, noise from extraneous sources, or for generalising the data to simplify and reduce variation. At Huff the ground surface exhibits a uniform slope that drops about 4.5 m across the village's 240 m width (an average 1.9 percent grade; Figure 1a). This gradient was eliminated through application of a large-radius (7.5 m) *high-pass filter* to "flatten" the landscape. All surface depressions (houses, ditches, bastions) thereby became negative in value with positive results representing local high-points (typically raised berms that once formed walls surrounding houses or mounds of excavated earth adjacent to the defensive ditch) centred about zero-valued 'neutral' ground (Figure 1c, d). Idiosyncrasies in this surface in the form of animal burrows, looters' holes, former excavations, and minor erosional cuts were next reduced through repeated application of an adaptive box filter (replacing deviant values with local means). The surface was then further generalized through several applications of a narrow-radius (0.5 m) low-pass filter (Lillesand *et al*., 2007). The outcome simplifies and better characterises the shapes of archaeological features of interest (Figure 1e).

The magnetic gradiometry data also contains nuisance elements that detract from the archaeological signal. Primary among these are robust dipolar anomalies that arise from introduced iron objects that litter the site. All were deposited post-occupation by the hundreds of tourists that visit each year, but they are relatively rare. As they represent a form of noise that will detract from subsequent processing, an experimental algorithm was developed for their removal: (1) large negative poles (< -4 nT) were isolated (through a reclassification operation), (2) large positive poles (> 4 nT) were next defined, (3) a distance buffer of small radius (< 1.5 m) was generated around the defined negative poles, (4) positive poles within that buffer were joined with the negative poles through a Boolean union, (5) the resultant dipolar areas were set to zero, the approximate mean of magnetic gradiometry data.

Finding houses

Initially, a template-matching approach was investigated to define potential houses algorithmically from the DEM. In this approach, a template is usually defined that corresponds to the approximate shape of a target; it is then passed over the entire raster centred cell-by-cell and its 'correlation' (expressed as a sum of cross-products) is assessed point-by-point (Kvamme,

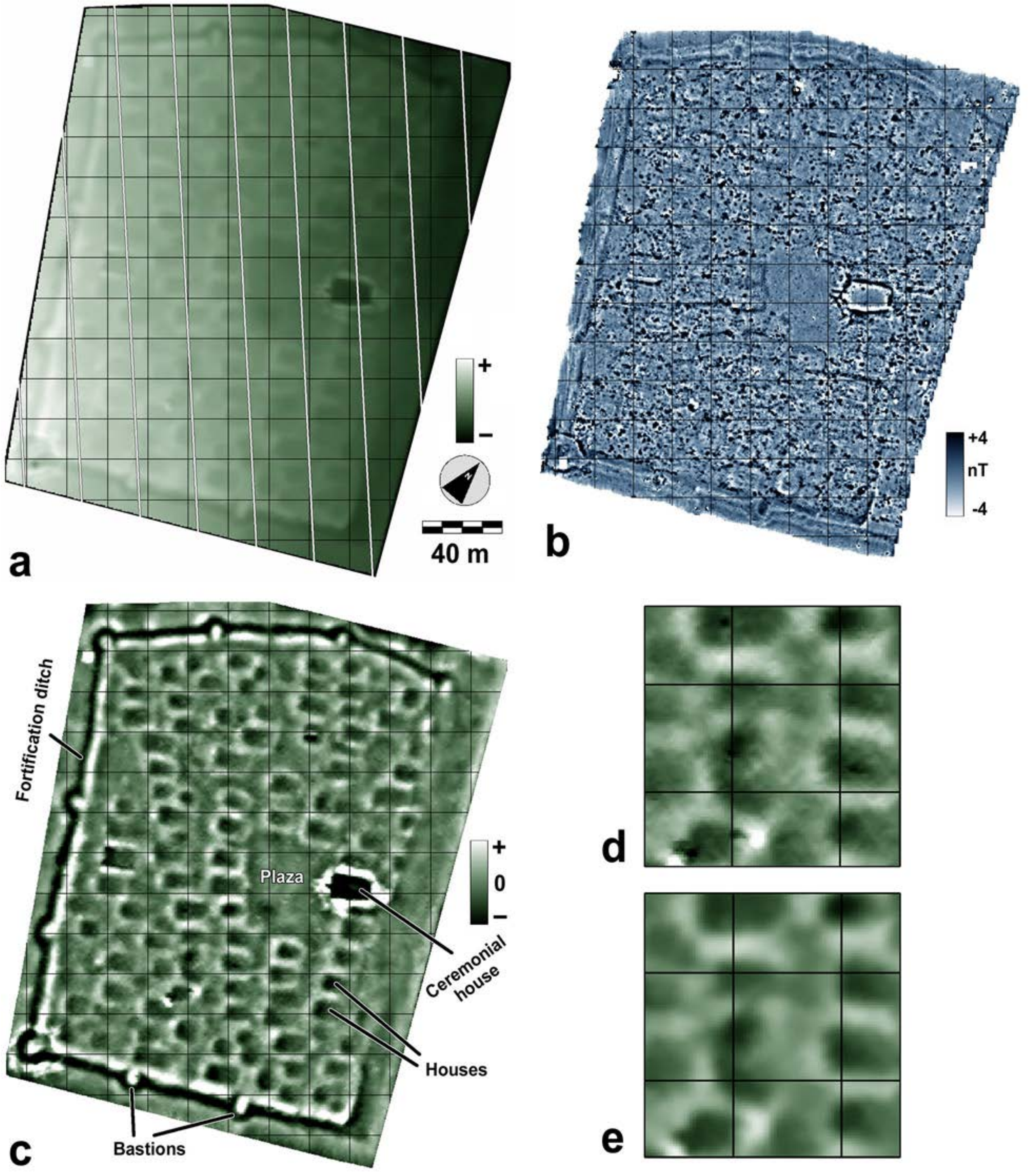

Figure 1. Data from Huff village: a) raw surface elevations with half-meter contours (white) showing the general slope gradient, b) magnetic gradiometry, c) elevation data after application of high-pass filter, d) close-up of raw elevation high-pass filtered data, e) close-up of elevation data after generalization by adaptive box filters and low-pass filters. The grid indicates 20 m squares.

2013; Trier *et al.*, 2009). High correlations occur wherever templates well-match the data. Three templates were devised: one matching the footprint of an 'average' house (floor coded -1; berm +1), a second matching the average long-axis cross-section, and a third the mean short-axis cross-section (Figures 2a–c, respectively). All performed well, particularly the second, but all falsely identified large ditch segments as houses (not an issue because they could be reclassified away by their too-large areas) and all failed to recognize several houses much smaller than the average size (Figure 2d).

An alternative and simpler approach was therefore investigated utilising a series of reclassification and

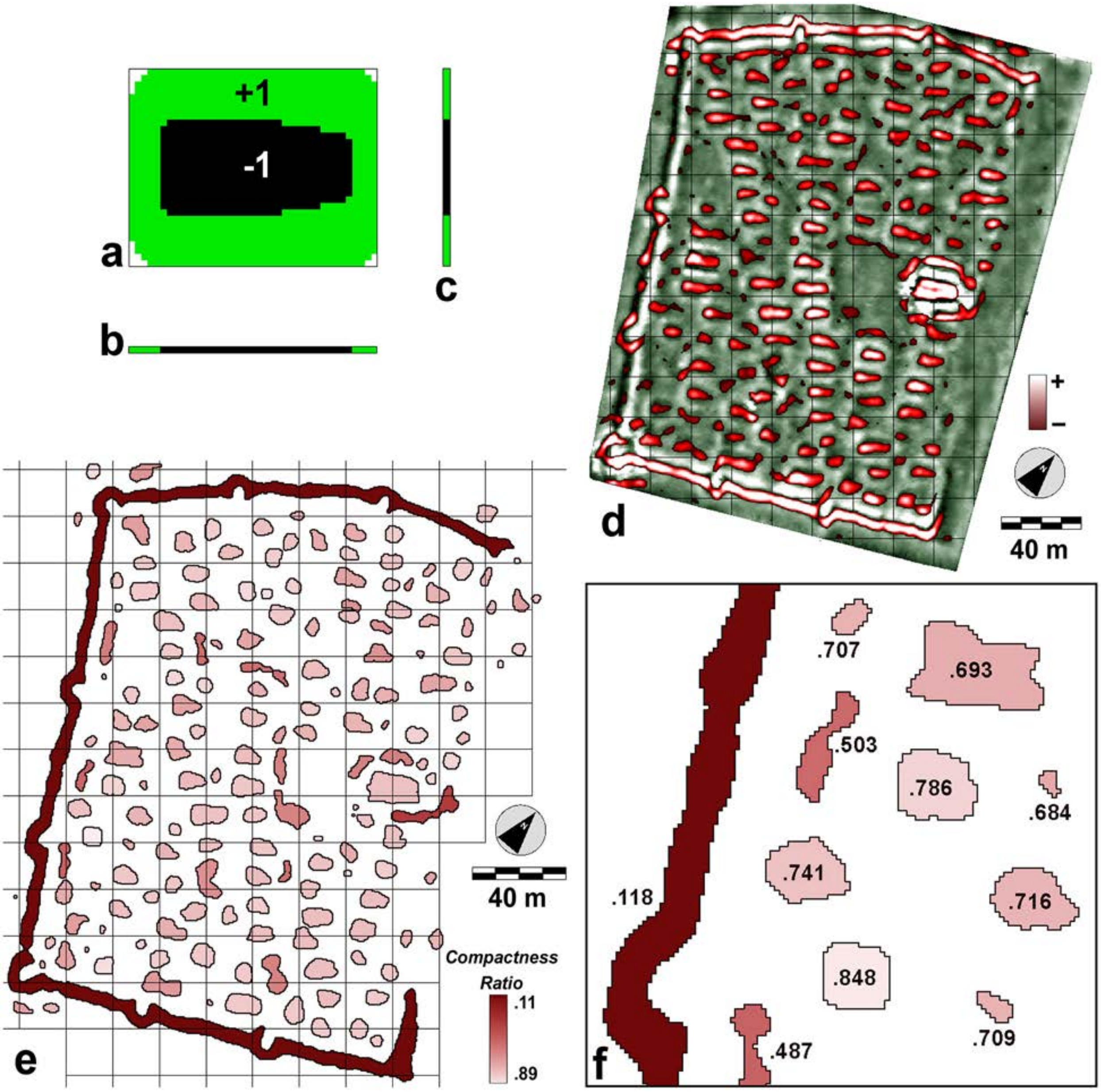

Figure 2. Defining landscape depressions: a) template for average house, b) house long-axis cross-section template, c) house short-axis cross-section template, d) filtering result by template 'b' shown atop DEM, e) polygons representing depressions in village surface scaled by compactness ratio, f) detail showing numerical values.

sub-setting operations. Reclassification tools identified all significant depressions in the generalized DEM (Figure 1e) below a threshold of -.06 m as *negative* polygons, including those associated with houses, ditches, remnant indications of animal dens, looters' holes, borrow pits, and small negative undulations that naturally occur in the village surface not removed by the generalized filtering (Figures 2e and 3a). A total of 171 negative polygons were defined. A *compactness ratio* was then calculated for each polygon: $C = (A_p/A_c)^{1/2}$, where A_p is the area of a polygon and A_c is the area of a circle having the same perimeter as the polygon (Davis, 2002, p. 356). The index approaches unity as a polygon approximates a circle; a rectangle or more often oval (due to erosion of the original rectangular surface forms) with the approximate shape of Huff houses generally yields $.65 < C < .9$; longer rectangles and polygons of highly irregular shape yield much smaller values (Figure 2f).

With ground depressions associated with houses typically measuring 6 × 10 m (about 60 m^2), those polygons with areas from one-half to twice that area were initially selected as potential houses. This set was then reduced by selecting compactness ratios in the Huff house range (i.e. $.65 < C < .9$) that permitted

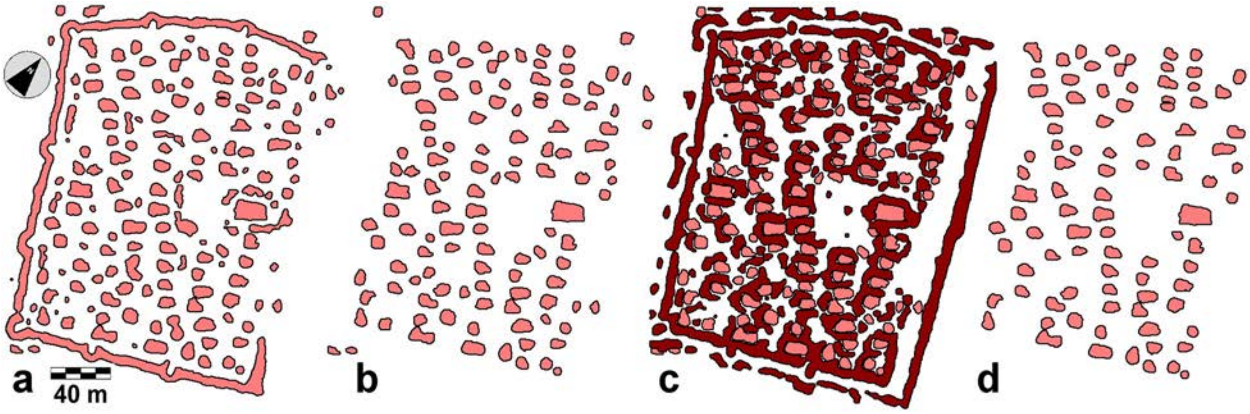

Figure 3. Processing steps in defining houses from DEM: a) all surface depressions (from Figure 2e), b) depressions of correct area and compactness ratio for houses, c) overlay of positive elevation polygons (dark) including house berms, d) potential houses defined by depressions with large areas of surrounding berms nearby.

inclusion of the many oval to near-rectangular shapes. While these steps zeroed in on likely houses with only 119 polygons remaining, numerous false positives were in evidence owing to several large depressions in the village landscape, possibly from soil borrowing (Figure 3b).

Focus therefore turned to the raised berms surrounding each house composed of sediments excavated from their floors during construction and former wall materials. A reclassification operation defined all areas in the generalized DEM (Figure 1e) greater than .04 m *above* the neutral background of zero as *positive* polygons (Figure 3c, dark polygons). Spatial proximity was employed to ultimately define houses as those polygons containing significant areas (> 20 m^2) of raised berms within a buffer radius of four meters. The final selection produced a good result with 91 potential houses defined, of which only three were false positives (Figure 3d). All three lacked indications of central hearths (see below), a required house element, but as it happens the hearths had been removed by prior excavation in two of them (Wood, 1967). The third false positive, although the approximate size and shape of a house, must represent a borrow pit below because it lacks a hearth. The defined houses are plotted in Figure 4.

Ceremonial house

Each Northern Plains village contains a larger structure for the performance of certain ceremonies, termed a 'ceremonial house' (Wood, 1967). This feature was defined by turning to the 'house' polygons and simply selecting the largest one (Figure 4). The ceremonial house measures approximately 220 m^2, while the next largest house is 106 m^2 and the average of the remainder is only 61.8 m^2 (as measured by surface depression size in the DEM, somewhat smaller than actual house sizes).

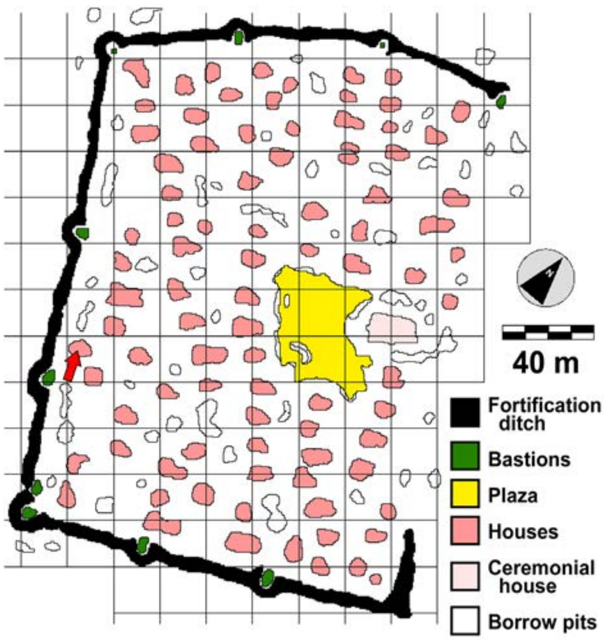

Figure 4. Archaeological feature classes defined algorithmically from the digital elevation model. Arrow points to false positive house reinterpreted as borrow pit.

Fortification ditch

This feature can be defined as the negative polygon in Figures 2e–f with the lowest compactness ratio (C = .118, due to its great linearity) or the largest area (2967 m^2) because of its sheer size relative to all other surface depressions. This procedure was successful with good ditch definition surrounding the village and each bastion is well outlined, important for their algorithmic definition below (Figure 4).

Borrow pits

Earth borrowing was a major activity in Plains villages because the sides of the houses were formed of built-up earth that was packed against a wooden and brush frame; in later periods the roofs of the earthlodges, which were dome-shaped, were also covered with earth (Wood, 1967). This requirement for earth led to the excavation of borrow pits within and near the villages. The full mapping of significant surface depressions (Figure 2e) *minus* the one associated with the fortification ditch (Figure 4) and *minus* those likely associated with houses (Figure 4) represent the best candidates for earth borrowing pits. Those greater than 6 m^2 (to eliminate ones likely associated with animal dens or looters' holes) are mapped in Figure 4.

Bastions

Unlike the foregoing village features, bastions are typically elevated above the surrounding ground, are oval-shaped, measure about 6 × 7 m, and are surrounded on three sides by a fortification ditch. They are clearly seen in the DEM of Figure 1 or in the mapping of the fortification ditch where they occur at nearly regular intervals of 50–60 m (Figure 4). Initially, tactics similar to those employed for house definition were investigated. A *reclassification* operation was employed to define all areas in the processed DEM (Figure 1e) greater than .15 m above the neutral background as *positive* polygons. Likely candidates for bastions included polygons from half to 1.5 times their projected size (about 30 m^2) and with compactness ratios above C = .7. Additionally, spatial context was employed to select only those polygons with significant ditch areas within a four meter radius. Yet, this procedure, and many variations, failed to yield results of high accuracy with a minimum of five false positives owing to the tall berm inside the ditch that included many local high points, some of which were contiguous with the high bastions.

The template-matching approach described earlier was therefore pursued using a 'donut' design with the 7 m diameter hole coded as +1 and the surrounding ring of four meters width as -1 (Figure 5a). When superimposed over a bastion in the processed DEM and cross-multiplied, the central region will yield a high positive product owing to its positive elevations and the negative ring will further increase the sum owing to the negative elevations in the ditch surrounding three sides. This template was passed as a filter over the processed DEM with the result that high sums were achieved over bastions, but also elsewhere along the ditch owing to irregular high points and along the high berms associated with some of the houses, particularly the ceremonial house (Figure 5b). After it was reclassified to indicate only high values (dark polygons, Figure 5c), only those with high proportions of overlap with a 1.5 m buffer of the fortification ditch (light polygon, Figure 5c) were retained (Figure 5d). The intersection of compactness ratios greater than .65, areas between 10–40 m^2, and positive elevations greater than .15 m identified all nine bastions successfully, but yielded one false positive owing to an unusual high point resulting from a back-dirt pile from an early excavation that was surrounded by an unusual ditch enlargement, also from the prior excavation (arrow, Figure 5e). The defined bastions are plotted with the other village features in Figure 4.

Plaza

The Mandan plaza is typically located near the village centre with the large ceremonial house located adjacent to it. A chief characteristic is its flatness and absence of cultural constructions. It is instantly recognised, for example, as a central large space devoid of features in the DEM or magnetic data sets (Figure 1). Its general region of location may be indicated by a distance surface computed *inward* from the surrounding defensive ditch and Missouri River shoreline to define a 'central' region (background continuous scale in Figure 6b). In addition, a distance surface may be generated from the ceremonial house (shown by contour lines in Figure 6b) in which the intersection of large distances in the former with short distances in the latter, point toward the general region of interest (background, Figure 6b).

To isolate the actual area of the plaza requires a more specific procedure. A 4.5 m radius *texture* filter was applied to the generalized DEM that computes a local standard deviation of elevations. The many surface depressions associated with ditches and houses, together with local rises caused by berms surrounding houses and ditches, all contribute to generate regions of high local standard deviations or texture (Figure 6a). Areas of low variation represent relatively uniform, low-sloping ground. A reclassification operation was employed to define low variance areas below a threshold of .03 standard deviations (polygons in Figure 6b). The largest homogeneous region must signify the region of the plaza which is also centrally located adjacent to the ceremonial house (Figure 6b).

Hearths

Hearths principally occur within houses, *all of which must include a centrally placed hearth*. Their identification can be difficult because anomalies generated by

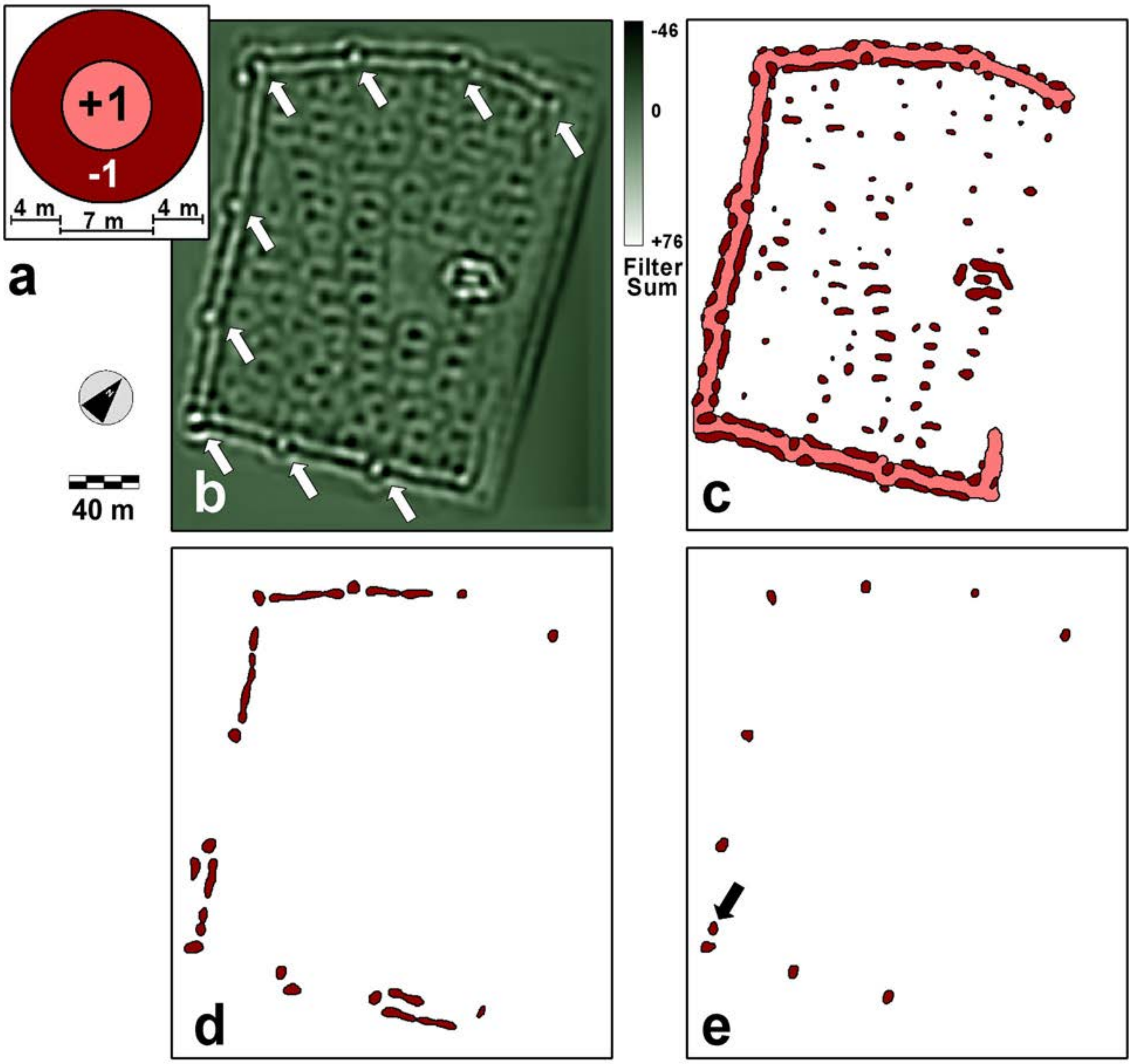

Figure 5. Isolating village bastions from DEM: a) filter template, b) result of filter applied to DEM with high results at known bastions (arrows), c) highest values as dark polygons overlaid on 1.5 m ditch buffer as light polygon, d) polygons with significant ditch buffer overlap, e) candidate bastions based on compactness ratio area and elevation (arrow shows false positive).

hearths in magnetic gradiometry surveys tend to be similar in size, form, and magnitude to those associated with storage pits. Both tend to be circular in shape and 1–2 m in diameter. However, statistical analyses of magnetic field strength consistently show differences between the two, with hearths significantly more magnetic (Bales and Kvamme 2005; Kvamme, 2007), although there is great overlap in their distributions. These criteria provide a start-point for the isolation of hearth-generated anomalies.

Anomalies greater than 3 nT were first selected because nearly all hearths fall in this category (Figure 7a). The compactness ratio then permitted elimination of those far from circular ($C < .65$) and those with areas in excess of 6 m^2 (Figure 7b). Spatial context and location within houses were next considered. House polygon centre points were generated and remaining magnetic anomalies within 1.5 m of house centres were isolated as hearths (Figure 7c). The result successfully defined at least one hearth within each defined house (and some have several, which agrees with archaeological findings that expose auxiliary hearths), but with three exceptions. In two cases the houses had been previously excavated and hearth materials (that could form magnetic anomalies) had been removed (labelled 1–2 in

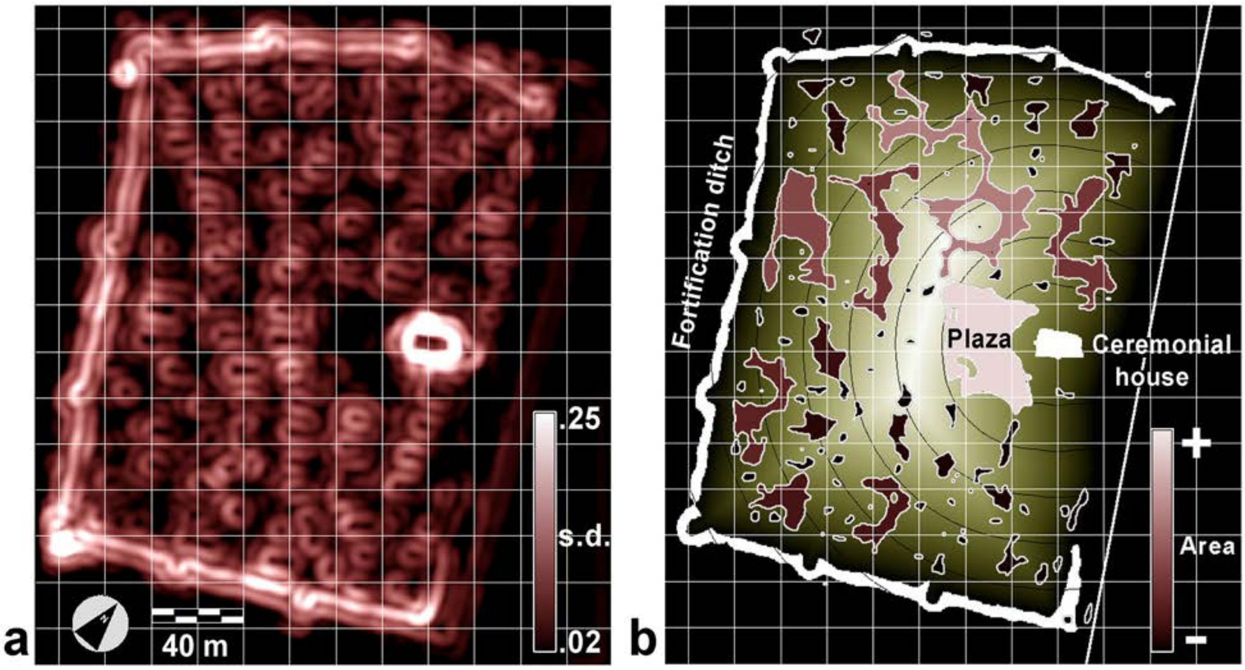

Figure 6. Definition of plaza through a) texture filter that computes s.d. of elevations in 4.5 m radius, and b) polygons representing featureless regions (s.d. < .03) scaled by area with largest the plaza. The plaza lies close to ceremonial house with distances indicated by 20 m contour lines; it also lies centrally as indicated by background distance-from-village-edge surface.

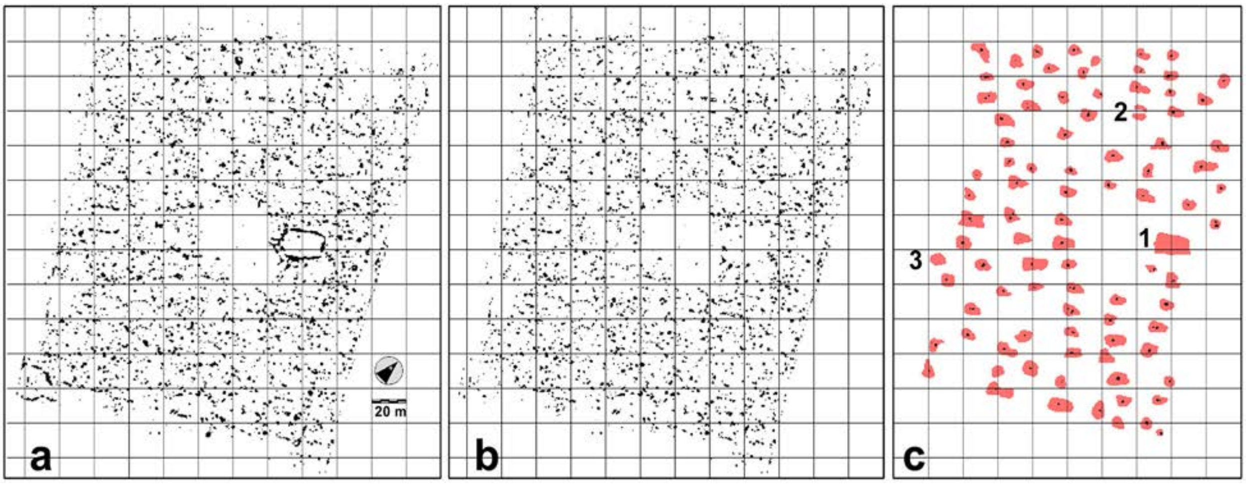

Figure 7. Identifying magnetic anomalies associated with hearths: a) all anomalies > 3 nT, b) those with small areas and more circular candidates, c) likely hearths associated with house centres. Polygons 1–3 lack hearths.

Figure 7c; Wood, 1967). In a third case a defined house at the village perimeter lacked a hearth, which means it cannot be a house (discussed earlier). The presence of a hearth therefore provides another criterion to be considered in house definition. This false positive house therefore was likely an earth borrowing pit, which sometimes can be as large as a house (indicated as ‘3’ in Figure 7c).

Storage pits

Procedures for storage pit extraction were similar to those employed for hearths. First, all magnetic anomalies with moderate to low magnetic field strengths (2-12 nT) were isolated. This was followed by sub-setting according to compactness ratios greater than C = 0.4 and areas less than 9 m^2. Spatial context was then employed to zero-in on known storage pit contexts.

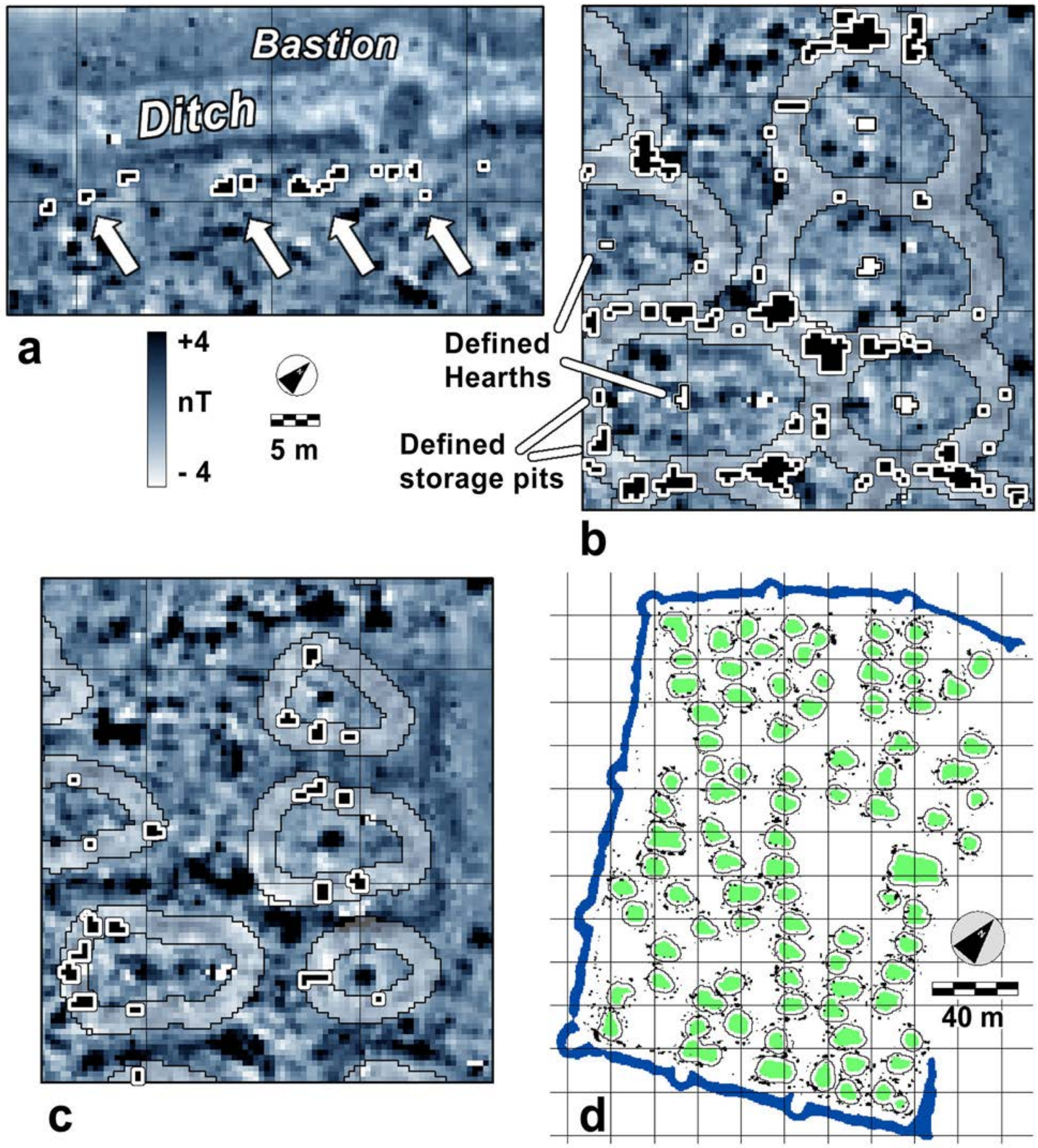

Figure 8. Recognising corn storage pits in magnetic gradiometry data: a) detail of ditch segment showing associated likely pits (arrows) within 7 m, b) 3 m exterior house buffers and defined central hearths (white) with storage pits surrounding houses (in black), c) 2.5 m buffers inside house interiors and identified interior storage pits (in black), d) all storage pits defined in village; solid polygons are houses defined by DEM while solid black lines indicate the 2 m radius buffer employed to more realistically represent their areas.

- A *fortification ditch pattern* consists of storage pit distributions along the interior edges of the defensive ditches *inside* the palisade line. Beginning with the foregoing selection criteria, those anomalies proximate to the ditch (within 7 m) were selected, for a total of 160 (Figure 8a).
- A *house exterior perimeter pattern* occurs adjacent to houses along their outside perimeters. Unfortunately, owing to surface erosion, houses defined by surface depressions in the DEM in Figure 4 are somewhat small (and more oval) compared to their actual floor plans, as revealed by excavations

(Wood, 1967) or magnetically (Figure 1b). House polygons were therefore expanded, through buffering, by 2 m. A 3 m buffer was then extended beyond these polygons and intersected with the foregoing pit selection criteria to define 921 storage pits within these regions (Figure 8b).
- A *house interior perimeter pattern* is similar, but occurs *inside* houses generally along perimeter spaces. Utilising the expanded perimeter buffer of 2 m, a 2.5 m buffer on its *inside* edge was generated and intersected with the initial pit criteria to define 373 interior storage pit candidates (Figure 8c).

The foregoing defines a total of 1454 subterranean storage pits within Huff village (Figure 8d). Such data, of course, have implications relevant to population estimates and agricultural productivity. With an average volume of perhaps slightly more than 1 m^3 (Wiewel, 2017), approximately 1500 m^3 of corn storage space is indicated by this analysis, which points to the potentially large population this village likely supported within its short span of occupation (Kvamme, 2007).

Summary and conclusions

The foregoing exercises were conducted to investigate the possibilities of automatic archaeological feature extraction algorithmically, for the most part using established and relatively simple GIS tools in a well-understood Northern Great Plains village. Obviously, there is room for vast improvements in such methodologies. The overall classification accuracy is good, with ready identification of the fortification ditch, plaza, and ceremonial house, and excellent indications of bastions, with one false positive (Figure 4). For the most part, the house classification also appears good from the DEM alone. A clear fault is that houses defined by DEM are too small by perhaps 30 percent and too oval in shape, generally caused by post-occupation erosion of the surface depressions. Distance buffering to make them larger might be one solution; a better approach probably lies in electrical resistivity surveys which defines house shapes and sizes accurately when conditions are right (Kvamme, 2003).

Working with magnetic anomalies associated with hearths and subterranean storage pits is more difficult, because they look much the same in shape, size, and magnetic field strength. The tactic of defining hearths near house centres worked, however, because houses must be associated with centrally placed hearths. Yet, auxiliary hearths also exist which are often placed off-centre within many houses (Wood, 1967) and there certainly were exterior fire pits in such villages. It is quite likely that a small percentage of the defined interior storage pits (Figure 8c) actually represent auxiliary hearths. Exterior fire pits might be defined by magnetic anomalies of very high magnitude, but this needs to be further investigated. The next step in this research is to take results developed here and apply them to other village data sets, a process soon to be undertaken. This investigation will permit further refinements and better understanding of a fuller range of variation in these sites.

Although conducted as an exercise with a well understood and small data set, archaeology is rapidly moving into the world of 'big data' where vast remotely sensed data sets, including LiDAR, air and space imagery, and ground-based geophysical surveys are becoming commonplace. Methodologies such as those investigated here will grow in importance simply because of the impossibility of trained observers visually examining data sets meter-by-meter to locate possible archaeological signatures. Procedures such as these will initially provide pre-screening tools that may considerably reduce the amount of labour and time needed to evaluate remotely sensed data sets. Eventually, as algorithms and accuracy improve, these techniques may become robust in themselves. At the very least they could point to potential areas where trained observers should focus.

Acknowledgements

Support of the State Historical Society of North Dakota for fieldwork at Huff village is acknowledged. Duncan McKinnon and Adam Wiewel assisted in the fieldwork that acquired these data.

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Mieko Matsumoto and Espen Uleberg (eds) 2018. ***CAA2016: Oceans of Data***
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
Oxford: Archaeopress

Interpolating 3D Stratigraphy from Indirect Information

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Abstract
Profile drawings in excavation reports tell the archaeologist about the structural arrangements, as well as the timely sequence of actions on site. Profile drawings by default only register the material distribution at the walls of the trench, and not within the trench itself. This can lead to misalignments of finds and therefore to misinterpretations regarding the associations and time-sequence of actions. Based on profile and material information, it is possible to estimate the distribution of the stratigraphic layers, thus allowing not only reasoning over the association of finds, but also to estimate the impact of potential structures and (human) interference on the material distributions. This is particularly helpful in assessing the likelihood of structures and their layout even in the (as yet) unexcavated areas. The algorithms presented here serve as a reasoning aid that can help by visualizing the material distribution and assessing the likelihood of different impacts and interferences.

Keywords: excavation profile, geospatial analysis, 3D reconstruction, material distribution

The problems with excavation reports

Excavation reports try to be objective records of an archaeological dig, capturing as much data as possible. Due to the complexity, the record must always fall short of the real information available, such as a biochemical analysis of every cubic inch. Even though the capabilities for recording data on site are constantly improving, such a level of detail will not be part of the standard excavation report anytime soon. The typical analyst has to make use of what little data are available, and the older excavation reports get, typically less data is available.

It was roughly 1950 before excavations were methodically recorded, let alone that additional data beyond the pure finds are reported. At around this time, the first profile drawings appear to record the overall layout and organisation of the trench. Such early reports, however, hardly ever consist of more than 2 vertical profile drawings — horizontal records are generally missing completely — so that little information about the overall material distribution is available (cf. Figure 1).

This makes it difficult to generate meaningful information about the layout of finds, their relationships to strata, and to each other. Finds are generally registered in 3D space, and the traditional approach is to assign them to a specific layer, which consists of 'projecting' them onto the profile walls. Finds thus assigned to the same layer are expected to be 'contemporaneous' (Figure 2).

This approach is not without problems though, as finds sometimes may not be uniquely assigned to one phase / layer if projected to different walls. In Figure 3 the 'X' denotes a single seal bone that can be associated with phase 2 when projected to the south wall and with phase 1 on the west wall — obviously this clearly impacts on the interpretation of the find.

To address this problem, this paper presents an approach to reconstruct the site based on the material properties and stratigraphic layout as registered on the profile drawings. In other words, we try to reconstruct the material distribution prior to excavation. As we shall demonstrate, these mechanisms are not only helpful for performing better geospatial analysis of the layout of finds, but also allow reasoning over different factors that may have impacted on the layout of the site — including potential secondary influences, such as human structures or climate conditions. Similarly, it can provide some insight into a non-excavated region.

It must be stressed that such a reconstruction cannot retrieve lost information (Gabbay *et al.*, 2011), but that it allows reasoning over potential influences that have contributed indirectly to the shape of the profile layers. The method presented here builds upon knowledge about the likely stratigraphic distribution of different material. The main goal of this work is thereby to keep

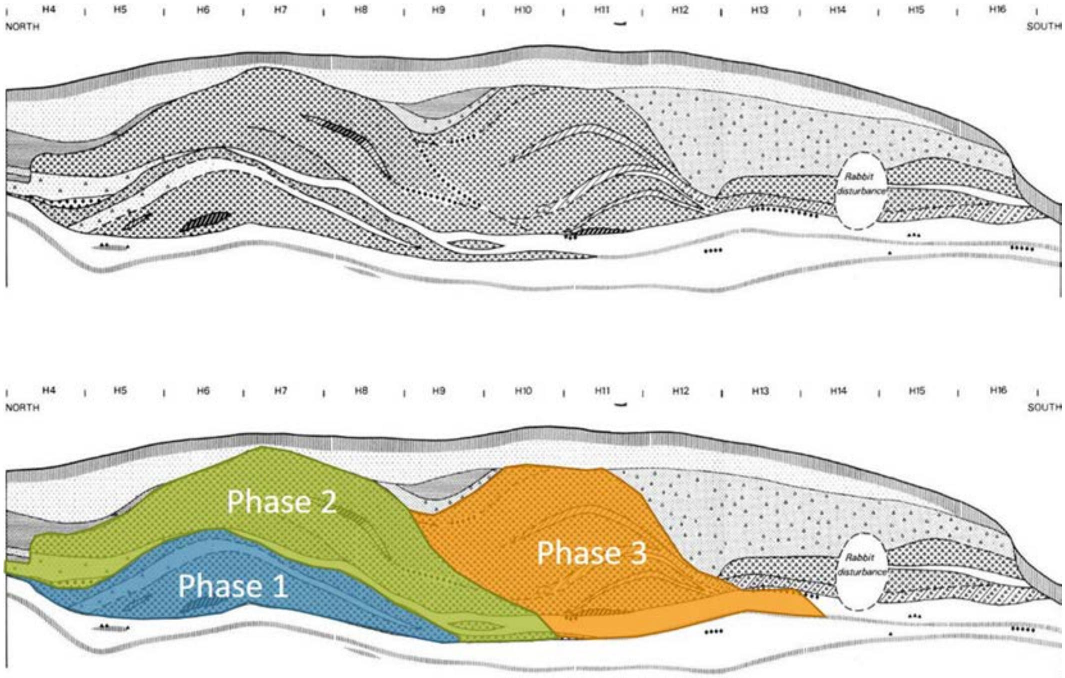

Figure 1. North–South excavation profile from Mellars (1987) (upper picture) and some potential stratigraphic layers / phases identified on this profile (lower picture).

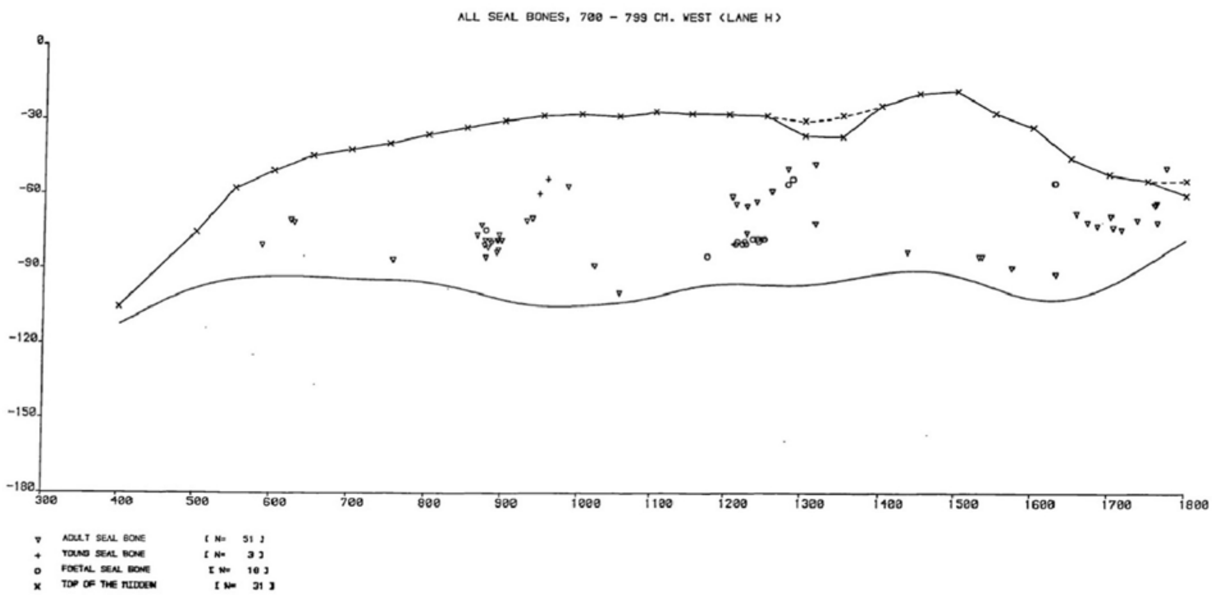

Figure 2. 2D projection of the find locations onto the profile walls — here: seal bone finds in Cnoc Coig (Nolan, 1986).

such information open and easily extensible to account for further aspects in the future. Currently, the work is at the level of a proof of concept.

This paper is organised as follows: section 2 provides an overview of the current approaches to reconstruct stratigraphic information and analyses of the according problems; section 3 elaborates the factors contributing to the layout of the site and thereby provides the foundation for the algorithm; section 4 builds-up the algorithm and explains the rationale behind it; section 5 will explain the current implementation status and future planned work; and finally, sections 6 and 7 discuss the value of the (current) algorithm in the context of a concrete example.

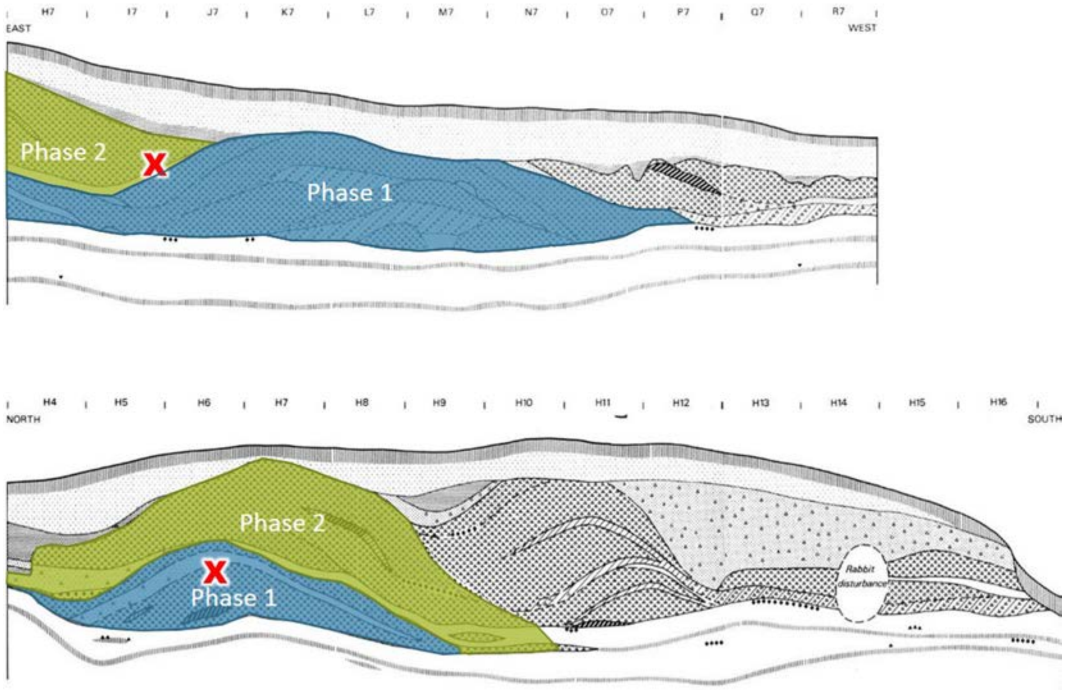

Figure 3. Exemplary find (seal bone) that can be associated with two different phases, depending on whether it is projected to the south (east–west) wall (upper), or to the west (north–south) wall (lower) (Mellars, 1984).

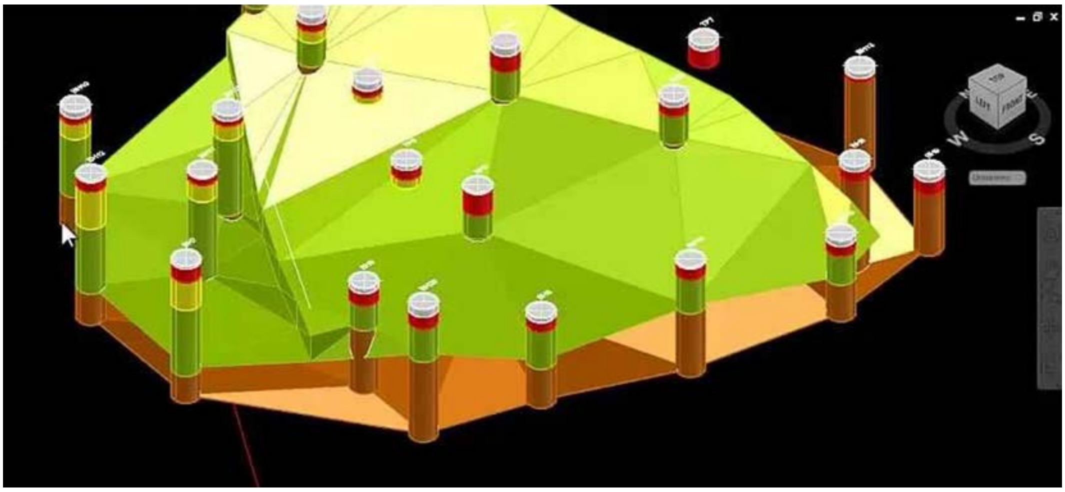

Figure 4. Layer reconstruction with Autodesk Geotechnical Module (source: Keynetix Ltd.).

Approaching site reconstruction

The problems of simple projection are obviously not new to archaeologists, and typically it is up to the archaeologist as to how to interpret relationships and potential clusters of finds. Some approaches, such as the Autodesk Geotechnical Module, compose a reconstruction of layers based on data from boreholes, which essentially 'connects the dots' between profile information. Together with the ability to visualize the site in 3D, this provides improved analysis over the simple projection approach (see Figure 4), but suffers in terms of quality as the number of boreholes (reference points) decreases.

But is this sufficient? Let us examine how material builds-up on a given site with — for the purpose of this work — a specific focus on shell middens, as they expose properties which are particularly useful for us.

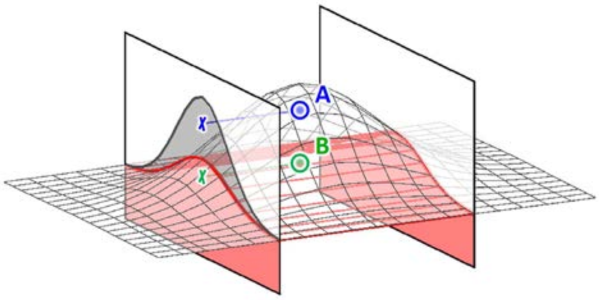

Figure 5. Simple connect the dots shape (red) versus actual shape (grey). Note the different associations of the two finds A and B.

Essentially, these middens build-up by people discarding shells from their food onto a large heap — and these piles can reach considerable sizes of up to multiple meters. From the nature of the material, shells slide down slope, and thus forming a very natural, sinusoid hill shape.

If we take two section cuts through such a site, it results in two bell curves that, when connected, would lead to a bridge-like surface that misses out completely on the build-up of material in-between (Figure 5). Accordingly, it is easy to see how two contemporaneous finds — A and B — would be associated with two different layers (Figure 5). Obviously, the error margin is highly dependent on the distance between the two section cuts and the material properties that determine the potential height of the pile up.

The shape is obviously conjectured, and indeed may have resembled a bridge (cf. section 4). The algorithm we discuss here does not claim to accurately produce the actual shape of the layer, but it can discuss the likelihood of layouts given different conditions on site. A bell-shaped curve on a section cut consisting of natural material will likely indicate a pile and the material properties tell something about the potential height, theoretically influenced by e.g. wind. Thus, not only can we evaluate the shape given different conditions, but vice versa we can infer some information about environmental conditions from shape. In the following, we will investigate the factors that determine the shape of a layer in more detail:

Factors contributing to the shape of a stratigraphic layer

It is relevant to distinguish *natural* and *artificial* types of layers in terms of their predictability: whereas *natural* strata will follow natural process and thus are subject to natural forces, such as gravity, *artificial* strata can principally take any shape at random. Obviously, even human- and animal-made structures follow a method, but their predictability implies additional knowledge about the structure (rather than just environmental factors). Without this knowledge, the strata may as well be considered random.

In the following we will investigate the influencing factors:

1) Natural processes

Most layers in an excavation site will have built–up naturally, and therefore will be continuous in shape. As a consequence their shape is predictable within a certain range. Even when piled up on artificial, human-made context, the natural layers will shape continuously. Thus, we can make at least the following general observations about accumulations of material:

- layers will be continuous in shape, partially predictable and will roughly follow the shape of underlying layers;
- layers are subject to the forces of the elements and thus will be shaped in regard to environmental conditions. Sediment, for example, will build up specifically in depressions, following gravity and will be indicative of loose/wet environments; brown decomposed soil will be highly compressible but less affected by gravity etc.;
- artificial strata can principally take on any shape but are still subject to logical constraints defined by the structure itself.

In principle this means that the shape of any natural layer can be roughly predicted on basis of the material that it's composed of and the surrounding conditions (context).

2) Artificial processes

Layers are also directly changed by human and animal processes, which can generally take two forms: structures or 'additions' on the one hand, and structural changes on the other. Essentially this means changes in the shape of the layer itself (postholes, mounds), or additions to the landscape that would otherwise not be there (hearths, buildings and so on). The latter will be embedded into the layer and will generally be recorded in the excavation report, which provides us with additional information about the shaping processes of the site. Secondary contexts may, however, be overlooked by the excavation, in which case, as noted, this information will be lost forever. Indirect evidence may, however, give an indication as to their existence (see below).

If the general structure of the artificial addition (or alteration) is known, this can be used to predict its shape — typically even in full 3D. Neolithic hearths for example have the tendency to be circular and flat (much like a campfire), buildings will, depending on period and location, tend to be circular or rectangular etc. If such information is available, the shape of the specific part of the layer can be estimated accordingly.

It should be noted again that artificial elements will directly influence the shape of the surrounding strata.

3) Influencing factors

We can also postulate a set of additional constraints and considerations that will help us analyse and predict the stratigraphic layout: whereas before we examined specifically each layer individually (though respecting the environmental 'shape'), we now will look at how they may influence each other. If, for example, a moist and a dry strata are visible in the profile, they will not touch, as this would lead to the moisture dispersing to the dry material, thus altering the consistency of the latter. Similarly, heavy dense material such as gravel will not rest on top of loose, deformable material, such as mud or soft soil, but will sink into it.

In other words, specific layers will not touch without influencing each other, which would be visible in the profile. Although this generalisation will not hold true in a larger context, it is generally a fair assumption within the closed vicinity of an excavation trench.

We can only provide an excerpt of all the factors involved in forming layers, many of which are indeed still not understood, see e.g. Crabtree (1971) and Bell *et al.* (1996) and would benefit from an in-depth physics simulation to understand the processes better. However, this is beyond the scope of this paper and instead we focus here on how to reason over shape *after* the processes have acted upon it:

An algorithmic basis for stratigraphy reconstruction

In fact, a straight-forward approach to calculating the material distribution would consist of, in a physics simulation, different influencing factors, ranging from environmental conditions (wind, humidity, etc.) to material properties (density, type, etc.), and then simulate how layers affect each other over time (compression, decomposing, etc.). But archaeological sites are open-world systems, i.e. multiple influences play a role in shaping their layout. Minimal effects can have massive impacts, as is the dominating claim of all chaos theory.

With an archaeological site we have a record of how the material accumulated and not a set of conditions for an empty site to simulate built up. The factors leading to exactly this build-up are infinite; and ending up with an even remotely similar distribution must be considered impossible. In principle, if we regard the material build-up and conversion as a mathematical (complex) function, what we are looking for is the inverse function that allows us to generate the conditions from the results — however this is not possible with complex (chaotic) systems.

Outline of the algorithm

Archaeologists and geologists can perform a mental reconstruction of a site using the profile information. It is already a great help for them to perform a simple projection of the excavation profiles onto the walls of a 3D rectangular box following the dimensions of the trench and therefore of the profiles (see Figure 6). Experienced people with good visual imagination can already get a rough feeling for how the profiles in Figure 6 are likely to behave and can even argue over the potential impact of specific factors such as the location of a find within that layer and so on.

This mental process is based on curve fitting and trend identification. We follow the same principle in the first step of our algorithm by using the recorded profile as reference input data. It is noted that geographical, let alone artificial layers, must not follow such trends. From the information about the shaping processes above, we can also say that curve fitting alone will be insufficient, as it generally does not take logical constraints into consideration, unless they can be expressed as concrete points or as part of the approximation function. We therefore choose a multi-phase approach incorporating different methods of strata reconstruction, consisting of both curve fitting and logical arguing.

Essentially the algorithm can be summarised as follows:

1. starting with the lowest layer, identify the set of points defining the strata boundaries;
2. encode additional information about the layer, such as finds and material properties;
3. fit the strata against a 3D curve (surface) using the additional information as attractors;
4. sanity check whether logical constraints are violated;
5. remove the last strata boundary from the total set.

The process is repeated from bottom up until the set is empty. Notably, changes in higher strata may affect lower ones as e.g. the pile-up will become unrealistic. This specifically means that the additional parameters

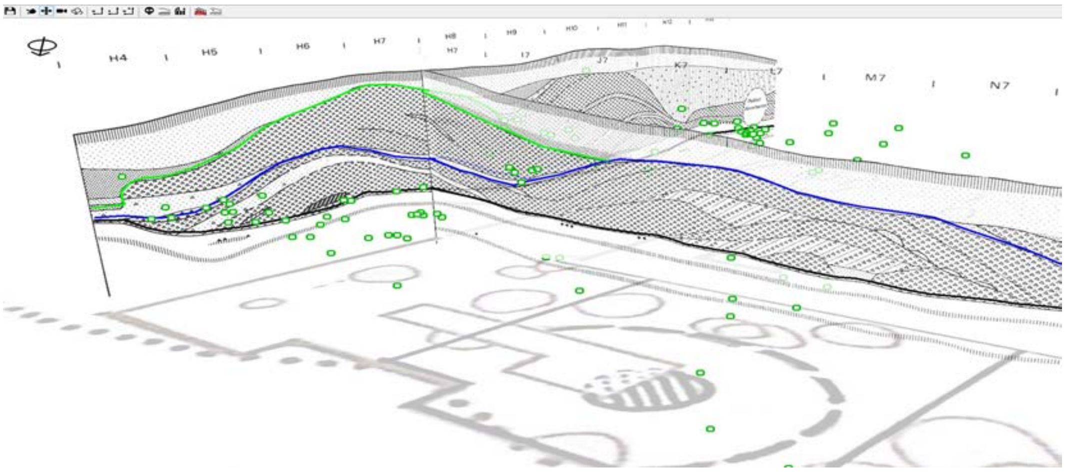

Figure 6. Putting the excavation profiles into 3d context (view of the current tool, green circles denote seal bones).

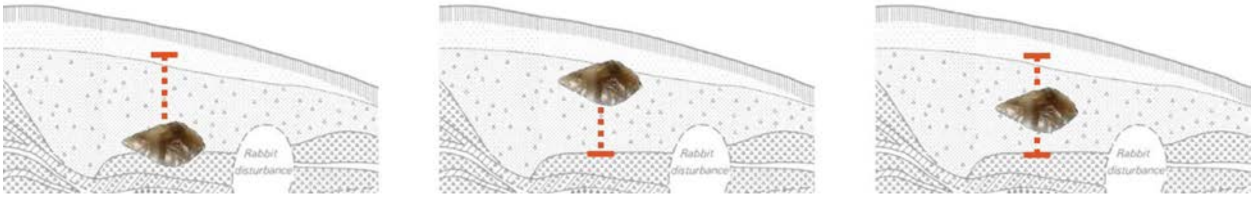

Figure 7. Finds as lower, upper boundary elements or layer attractors (from left to right).

alter, since the measured profile is fixed. As will be discussed below, if no matching solution can be found, we observe a high likelihood for artificial (human or animal) processes at work.

Step 1: Reference point set(s)

Our primary reference point set is the excavation profile, which denotes the outline of the material layers at the location of the section cut. As noted, we act on the surface, rather than on the material distribution itself, so that two boundaries form the strata that we want to reconstruct. This means that two surfaces form the actual layer. Layers don't have to span across the whole site and may in fact be lenses. Typically, the archaeologist will denote which layers and phases they associate with which part of each profile drawing, allowing us to infer how the drawings relate to each other.

Step 2a: Attractors

Finds within the trench, when they can be clearly associated with a specific layer (which is not always the case), help with evaluating the shape of the layer: they can be 'forced' to relate to a layer by making them an '**attractor**' within, i.e. so that the algorithm tries to ensure that the find is between the two layer surfaces (upper and lower). Let us look at that in more detail:

Frequently a find denotes the boundary of a layer, such as when a structure was built on an older layer and a new layer accumulates over and around. Depending on the material (of the find and the layer), or the accumulation process, the find may intermingle with the layer, e.g. by sinking into soft mud, to the ground of a lake or by further accumulation around it, such as a discarded object in an 'active' shell midden. As such, the according reference point (location of the find), must be considered an (1) upper or (2) lower boundary, or in fact only (3) an indicator that the layer passes around it (Figure 7). Hence the point is either part of the upper (1) or lower (2) surface, or we can state for the lower surface that $z_{surf} < z_{find}$ and for the upper accordingly that $z_{surf} > z_{find}$ with $(x_{surf}, y_{surf}, z_{surf}) \in$ lower, respectively upper surface.

Step 2b: Material properties

As noted, layers build up through the accumulation of materials (leaving slower geological processes aside). Natural processes will influence the shape of the layer (cf. section 3). For the algorithm we must encode these properties in mathematical form — these properties are still being elaborated, but due to lack of space we can only provide an excerpt for selected material here to demonstrate the methodology for how such properties can be expressed. In the following we assume that $f_{upper\ surface}$ and $f_{lower\ surface}$ encodes the shape of the upper and lower boundary of the layer, respectively:

- Rigid material (wood, metal) will form a straight layer until decomposed, which depends on environmental factors such as acidity. With no loss of generality we can thus say that for any layer of rigid material $f'_{upper/lower\ surface} \approx 0$ at any point;
- Loose material (gravel, sand) will be affected by gravity, i.e. tends to accumulate in hollows, rather than on peaks. In other words,
- $(f_{upper\ surface} - f_{lower\ surface}) > \delta$ for all points where $f'_{lower\ surface} = 0$ and $f''_{lower\ surface} > 0$, respectively,
- $(f_{upper\ surface} - f_{lower\ surface}) < \delta$ for all points where $f'_{lower\ surface} = 0$ and $f''_{lower\ surface} < 0$,
- with δ being a material and environmental specific indicator rather than a concrete value.
- Similarly, compressible material will be affected by the forces acting upon it and thus by the material properties of the upper surface, so that depending on the material within and above the layer we can state that
- $\gamma_{max} > (f_{upper\ surface} - f_{lower\ surface}) > \gamma_{min}$ for all points, where γ relates to the compressibility factor and forces.
- Etc.

Step 3: Surface fitting

Surface fitting essentially means adapting a series or function to the given points in the data set. Typically, we use the 'least square approach' that squares the distance between $f_{surface}(x, y, z)$ and the given (x, y, z) of a specific point (cf. Figure 8).

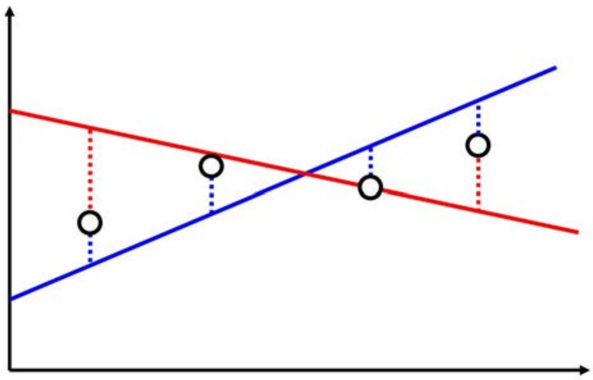

Figure 8. Two curves fitted against four reference points (circles). The vertical distance (dotted lines) denotes the error of the fit.

This approach is not entirely fair, as the real deviation is the distance between the point and the orthogonal projection onto the curve, although this leads to a minimal error.

The total error to be minimised is therefore

To identify the minimum error, we can use the derivative of the function with respect to all parameters in $f_{surface}$. We can obviously use the information from steps 2a and 2b to manipulate the shape of the surface: finds add data-points to the set of reference points, or provide delimiting boundaries, whereas material properties provide additional constraints on the function (respectively its derivatives).

As we build up layers bottom up, we can also add constraining criteria such as $(f_{upper\ surface} - f_{lower\ surface}) > 0$ at all points, meaning that the upper surface can never go below the lower surface. Notably, this may be an indicator for either the lower surface being inaccurate, or the upper surface ending here (cf. step 4).

Step 4: Global verification and optimisation

The global error optimisation curve fitting process can produce high local error — vice versa local minimisation can lead to a high global error. The typical curve fitting (annealing) process thereby treats all data as points to minimise the error (see above) and not as hard constraints, in the sense of that the curve has to fulfil the respective condition. Failing these constraints is not per se an error, though it indicates a problem in the (expected) surface shape. For example, an upper surface boundary residing for a large area *under* the lower boundary demonstrates that either the material properties are set wrongly, the lower boundary is miscalculated, or that the respective strata probably does not extend over the whole area. Logical constraints may also be violated, e.g. when wet and moist material would intermingle thus altering the (recorded) properties.

The interpretation of such errors reflects the analysis potential of the tool: the higher the error, the less likely the shape distribution is correct and therefore that all parameters have been appropriately set. By changing specific properties, such as find assignment etc. a more likely distribution and layout can be identified.

The choice of action thereby relies mostly on human expertise and reflects exactly the type of reasoning the algorithm is beneficial for (cf. section 7).

Step 5: Repeat

Steps 1–4 are repeated with all layers denoted in the profile walls from bottom up. Note that upper layers and their shape may impact on lower ones at any time, e.g. if a large amount of material rests on a compressible layer, thus affecting its layout in a manner unpredicted by the pure material accumulation itself. The algorithm may therefore have to iterate down from the last calculated layer to assess the impact (and hence correctness) of the underlying strata. This is essentially a special form of property adaptation as discussed in step 4, but may be applied automatically following the constraint definitions above.

Error discussion

It must be stressed again that the promoted algorithm can only 'guess' the actual material distribution. It can thus be used for the assessment of the likelihoods under different conditions, thus providing indicators for the layout and probabilities for different effects, e.g. if certain environmental conditions are unlikely to generate the layout recorded.

The error of the reconstruction thus originates exactly from this aspect: as the algorithm can only reason over likelihoods, it implies a deviation by nature. For example, the pile–up in Figure 5 may indeed have the shape of a bridge (see section 2). Besides for material properties, environmental conditions and the events at a site contribute to the shape of a layout, as discussed above. For example a shell midden can be accumulated by the people piling up the shells in a specific location or in a specific shape. In general, the more information — i.e. the more section cuts — that are known, the better the quality of the inference.

Current status and open work

The toolkit is in an early stage and the base algorithm is implemented primarily in MatLab to evaluate and assess quality and correctness. As the work has only recently started, we cover few material types, with a focus on shells, as they exhibit controllable properties and can be compared against existing results both from modern as well as early excavation periods. Additional material types will be investigated and parametrised as the development progresses. In the long run, the algorithms will be integrated in GIS tools to address the typical working environment of archaeologists.

What is of more interest here are the additional features planned and the value offered by them, in particular a more detailed physics model that can simulate the effect of different conditions — specifically structures — on the layout better, and improved spatial analysis mechanisms that take the layer shapes into consideration. An initial version of the spatial analysis is already incorporated into the current tool allows filtering finds with respect to the layers they are assigned to — a current extension to cluster finds on basis of type and (relative) distance within a layer is in beta.

A complete physics simulation is not sensible as it adds complexity at no benefit (see preceding section) — however a physics simulation would nonetheless be beneficial for analysis of different impact factors and their consequences. With the pure material inference we can achieve a 'natural' distribution of layers with the general environmental impact — artificial interference (see above) can thereby not be respected: obstacles, artificial and natural, will impact the distribution of material but cannot be simulated by the calculation as it assumes a continuous surface. With this information disruptions can be identified by deviations between the calculated surface and the recorded facts.

We are currently working on taking the impact of obstacles and structures on the material distribution in the simulation into consideration. For example, a wall will lead to material piling up against it, and stakes and poles will accumulate material around them. Such factors will not only disrupt the surface, but also will affect the shape in the first instance. Similarly, influences post material accumulation, in particular removal (including decomposition) of aforementioned obstacles, will shift and disrupt the layers a second time. In this specific case, even with no other evidence remaining, the (re)distribution of layers and their shape can give indicators for the original shape of the obstacle, when it was added, and respectively removed.

Similar processes can be used to analyse the distribution of finds and their location, so as to assess the effect of environmental conditions on the distribution, for example by sliding down a slope, being washed away by water etc. as e.g. happened in the Tollense valley in Germany (Curry, 2016). Such effects will obviously change the distribution and thus interpretation of the finds. The ability to assess the original layout is therefore of high value for any archaeological analysis.

Notably, as with the shape of the stratigraphic layers, the problem belongs to chaos theory and therefore cannot be calculated in reverse, meaning that no unique original position can be identified (Çambel, 1993; Hoover and Hoover, 2012). However, again, probabilities in particular for short distance effect can be assessed, such as to whether the material properties could have led to intermingling.

Revisiting Cnoc Coig / interpreting the data

We applied the algorithm presented in this section to a Mesolithic shell midden site "Cnoc Coig" on Oronsay (Mellars, 1987). Finds in Cnoc Coig comprise, next to the

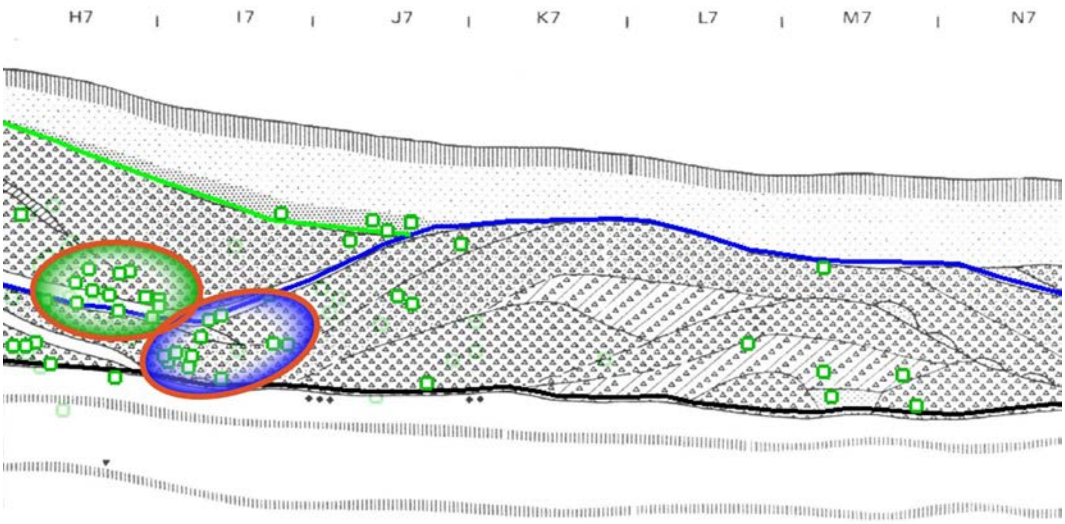

Figure 9. Seal bone finds associated with two different phases according to the projection method. Green relates to phase 2, blue to phase 1, cf. Figure 3 (based on Nolan, 1986).

shell debris, equally human and animal (birds, seals) bones (Nolan, 1986). There are also indicators for a temporal structure on site, which left little other signs than the post holes beneath the lowest shell layer (*ibid*).

The site has been subject to extensive spatial analysis of the finds following the projection approach discussed above for assigning finds to phases and identifying clusters (*ibid*). Excavation started in the early 1970s and the records are generally limited to two profile walls per trench, see Mellars (1987). Nolan added additional surface elevation information in his report (Nolan, 1986), yet no further phase layouts are available. When applying our algorithm, we identified that some of the find clusters are likely to relate differently to the identified phases than assumed by Nolan, leading to the conjecture that either phase assignment or clustering may be incorrect — the former being unlikely due to the clear indicators for phase separation (Mellars, 1987). Obviously, we must bear in mind that the algorithm provides indicative data only and thus this is less criticism on Nolan's approach, but a basis for reinterpretation of the data.

Following the traditional projection of finds onto the trench walls, it can be quickly seen that, for example, the seal bone finds highlighted in Figure 9 are clearly associated with two different phases, as they are separated by the blue line, which demarks the upper boundary of phase I according to Mellars (1987). However, if we take the full context, and in particular the likely distribution of debris into consideration, as suggested by our algorithm, we note that this distinction is far less clear. In fact, our algorithm associates far fewer finds within phase 1 than the projection method would suggest: Figure 10 and Figure 11 clearly show that the cluster assigned to phase 1 in Figure 9 is more likely part of phase 2, as phase 1 likely slopes down before reaching these finds. This would suggest that rather than 2 clusters in 2 phases, these finds probably form one single cluster contemporary in one phase. Other clusters indicate the opposite, namely that while they correlate spatially, they may not relate temporally. This demonstrates not only a longer persistence of certain foodstuff, but also may be indicative of regional activities and potentially even temporal memory and assignment of locations to specific eating habits or groups (Predoi, 2016).

Furthermore, what is interesting is the fact that a round structure as indicated by the find of postholes on the ground (Mellars, 1987) would most likely influence the material distribution since it would block debris, if it had actual walls. The distribution of shells in Mellars' report do not seem to indicate such an influence, as Mellars reports no deteriorated wooden remains in the shell layers, as would most likely be visible if the structure was permanent. The finds and the algorithm thus seem to hint at a temporary structure that was added during a later phase and removed again. Again, this is indicative only, and the algorithm for structural impact has not been fully developed at the time of writing this.

The full discussion will be published separately in the future (Predoi, in preparation). As for now, however, the preliminary results already make it quite clear that a lot of information is still to be discovered at Cnoc

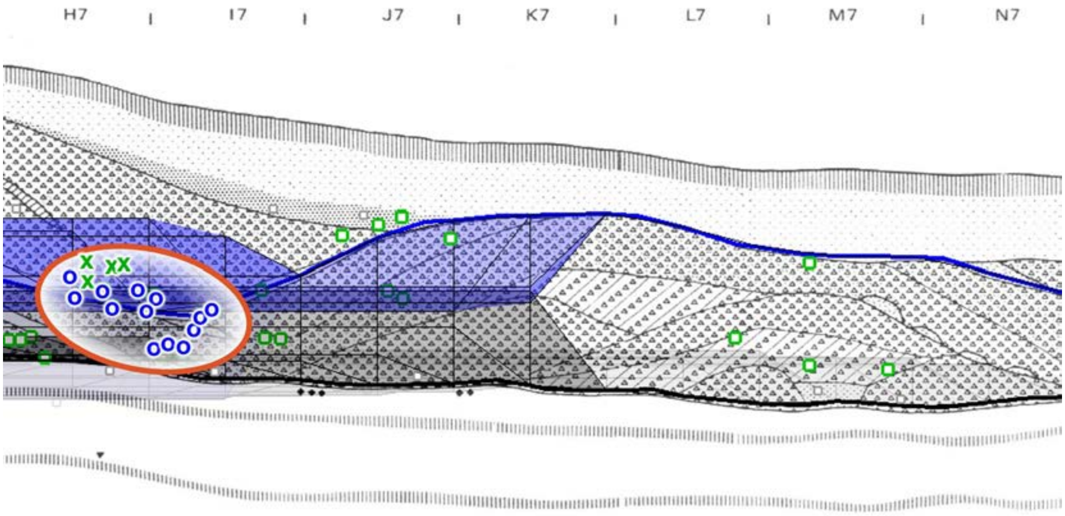

Figure 10. Seal bone finds associated with phase 1 (cf. Figure 1) according to our algorithm. Blue circles denote seal bones associated with phase 1, green crosses with phase 2. It can be noted that way less finds are associated with phase 2 than in the projection method (Figure 9).

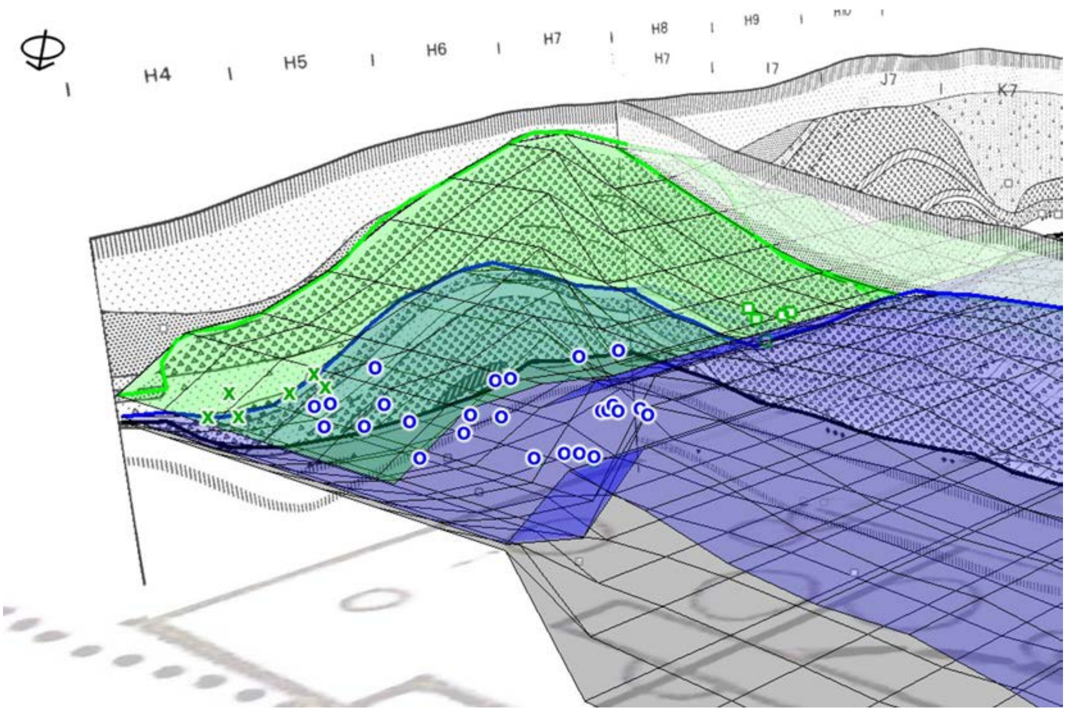

Figure 11. Same as Figure 10 but represented in 3D.

Coig, and there are good indicators that further finds and structures remain as yet unexcavated. Revisiting Cnoc Coig may thus be sensible for multiple reasons (see also Milner and Craig, 2009).

The value of reconstructing stratigraphy

Stratigraphic analysis is essential for any archaeological site: not only does it provide context for finds, but also insight into the activities at the site. Typically, this analysis is based on simple projection towards the profile walls, and/or on expertise of the archaeologists, which requires in-depth knowledge about the material behaviour, the site and a good visual imagination. GIS tools can support visualization with (typically) a simple connect-the-dots like method, which already greatly supports this analytical process.

However, as we have shown in this text, the projection and linear extrapolation method can lead to ambiguous if not even wrong assignment of finds to phases. Notably, we primarily refer to excavations that were insufficiently recorded, i.e. where finds are not registered with the appropriate phases or strata — however, identifying the appropriate phase in predominantly homogeneous material distribution, such as shell middens, at the time of excavation is difficult at best and may benefit equally from the approach discussed in this paper.

The approach is not constrained to reconstructing excavated areas — it can in principle make educated guesses into the as yet unexcavated area and its probable material distribution. As we indicated, given enough information about the physics at a site, including material type and behaviour, one can also estimate the probability of (hidden) structures — or more correctly: disturbances of the distribution. Such indirect influences, as well as how to make use of additional information sources, such as GPR, is subject to ongoing work and will be published in future papers as the tool evolves.

That said, the tool offers only a probability of material distributions given different parameters and thus primarily serves as a basis for discussion about different site layouts and influencing factors, such as environmental conditions (weather, climate, wind, etc.), but also potential (human) interventions etc.

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Closing a Gap with a Simple Toy: How the Use of the Tablet Affected the Documentation Workflow during the Excavations of the Rozprza Ring–Fort (Central Poland)

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Abstract
During the excavations of the medieval ring-fort and motte in Rozprza, 2D and 3D photogrammetric documentation and integration of research results into the GIS were widely used. They allowed for elimination of traditional forms of hand-drawn field documentation. It was particularly important in extremely wet conditions of the excavations of moat and subfossil palaeochannels. Agisoft PhotoScan software and the QGIS georeference module, as well as a set of open source graphical raster and vector applications were used. A proper organisation of the fieldwork and the use of a popular Android OS tablet helped to close a gap between acquisition of data and its time-consuming processing in Photoscan, as well as its description and preliminary interpretation. Hence the field documentation based on 3D techniques became a series of steps implemented routinely after the exploration of subsequent stratigraphic units.

Keywords: photogrammetry, digital documentation, medieval archaeology, moat excavation, stronghold

Introduction

Methods of 3D documentation (Tokmakidis and Scarlatos, 2002) of archaeological sites have been developing very rapidly since the beginning of the 21st century (for example Callieri *et al.*, 2011; De Reu *et al.*, 2013; Ferdani *et al.*, 2016; Sordini *et al.*, 2016). At present, they are not only part of technological advances in archaeological research, but also a significant methodical and organisational challenge. The use of 2D and 3D photogrammetry methods such as ‘Structure from Motion’ results in much more objective documentation than that prepared manually. It is also a significant improvement in comparison with traditional photography, which is fraught with multiple problems associated with lens quality and image distortion, perspective deformations and the lack of ability to read metric data from photos. This significant change reduces the role of traditional subjective and time-consuming manual drawings. Furthermore, it considerably shortens the process of obtaining data in the field. On the other hand, it requires more time for digital processing (it may take hours to produce a 3D model). This is an issue of great importance during the fieldwork. In order to do the work methodically, it is indispensable to carry out an inspection of results of already documented features, structures and stratigraphic relations, before moving on to the next stage of exploration. Archaeological exploration is always an irreversible destruction of these structures. Moving too fast in exploration could result in the loss of important information.

Some remarks from ancient history

The gap between the data acquisition stage and the availability of a fully-fledged model is not a completely new phenomenon. Similar challenges were part of traditional archaeological photography of the pre-digital era. In the pre-digital era, it usually took time to transform latent images on the photographic film into a visible image and to make it permanent and useful. No matter whether a professional commercial studio with specialist equipment or a more amateur self-developing approach was used, it took some time before the documentation could be viewed and evaluated.

Technical methods to build orthophotomaps with the use of analogue photos already existed in the first half of the 20th century, and were extensively used in civil and military applications. In Poland, these methods were used in archaeology for close range photogrammetry as early as the 1970s. This technique was however extremely time-consuming, required the presence of specialists and caused numerous difficulties in the process of interpretation of the obtained documentation. Therefore it was not used on a wider scale. This is why for years photography was only supplementary in archaeological documentation, which was fundamentally based on hand drawings, prepared directly in the field together with description and interpretation.

Digital (r)evolution and heritage standards

The use of digital photography for photogrammetric documentation started in Poland in the early 21st century (Gołembnik and Morysiński, 2004; Gołembnik, 2003; Tyszczuk, 2006). It was mainly based on the application of two-dimensional photogrammetry, combined with CAD and GIS software (Czajkowski and Gładki, 2004; Urbańczyk and Żukowski, 2011). At the same time methods of documentation based on 3D laser and optic scanning began to be used.

In our fieldworks, we have been using 2D photogrammetry based on open-source graphic and GIS software (such as Gimp, Inkscape and QGIS with its georeferencing module) since 2008, when we commenced our excavations in Ostrowite (Sikora and Wroniecki, 2014). Since 2011, we have started experiments with image based 3D modelling, using very basic applications, such as Bundler (Snavely *et al*., 2006), PMVS/CMVS (Furukawa *et al*., 2010; Furukawa and Ponce, 2010), Meshlab, as well as Microsoft Photosynth (Snavely *et al*., 2007; Microsoft Photosynth, n.d.), Arc3D (Vergauwen and Van Gool, 2006) and 123D Catch (Autodesk, Inc., 2016; Chandler and Fryer, 2013). It must be mentioned that in most cases the quality of obtained models was insufficient, and the workflow and interface of some of them were quite difficult for inexperienced users. Some of these applications required access to the Internet, as calculations of 3D models took place on external machines. Securing Internet access of a proper speed is not always possible in the field. An additional problem was that obtained 3D models were not georeferenced. Georeferencing required additional software and even then it was difficult to find a real advantage over digital 2D ortophotographic documentation. In 2014, we started using Agisoft Photoscan which turned out to be a solution to a number of previously existing problems:

1. The program is easy to use, even for an inexperienced user, and the whole process of obtaining models is automated. Only in a limited number of cases it is necessary to manually establish control points in order to tie input photos.
2. It produces high-quality models with detailed texture.
3. The 3D models can be georeferenced directly in the program, using a selected reference system.
4. The program is able to produce georeferenced orthophotos (orthomosaics).

Furthermore, 3D documentation which is obtained in this way is very detailed and allows for experiments, such as introducing 3D GIS (e.g. Berggren *et al*., 2015; Da Silva *et al*., 2016), and reconstructions in 3D graphical applications or use in virtual reality. However, it should first of all meet standards established by local heritage institutions. In Poland such standards are stated in the Act on the Protection of Monuments and the Guardianship of Monuments (orig. *Ustawa o ochronie zabytków i opiece nad zabytkami*; Dz.U. 2003 Nr 162 poz. 1568) from 2003 and are enforced by local Offices of Monument Protection. More detailed guidance was prepared in 2004 by the National Heritage Board (*Narodowy Instytut Dziedzictwa*) as Standards for Methods and Documentation of Archaeological Excavations and for Report Preparation (orig. *Standardy metodyczne i dokumentacyjne badań archeologicznych i opracowań ich wyników*). This 9 page long guidance offers a detailed explanation of norms expected by officials:

Documentation may be created with digital techniques (e.g., plans and sections created automatically based on data transmitted directly to the computer from the total station, digital photographic documentation), but it should be printed (available for inspection during the excavation), and should be easily obtainable in a printed form in the future. (...) All other forms of documentation (e.g. video recording, photogrammetric documentation, etc.) are welcomed as additional to the above documentation requirements. The use of the most recent technologies to improve the form of documentation of archaeological sources is recommended.

The official guidance allows digital documentation techniques as well as photogrammetry, but they are treated as additional to traditional, graphical, hand-drawn or at least printed documentation. Therefore, we can either stay with the traditional field drawing or we can use photogrammetry to create 2D printed documentation. It also means that any attempt at using digital tools which produce results that cannot be printed (such as 3D GIS), will always be treated as an additional 'decoration'.

It should be pointed out that the use of digital documentation methods in Polish archaeology is far from routine. There is a widespread use of digital photography, sometimes digital image processing and GIS software, but the on-site documentation process is dominated by traditional hand-drawing. The reasons for this are not only legal and organisational issues, or the conservatism of some archaeologists, mainly of the older generation, but also a commonly articulated problem of the 'lack of interpretation' in photogrammetric documentation. Photographic record does not clearly demonstrate borders of contexts, which seems to be extremely important in the case of multi-layered and multi-phased sites. This argument is mainly due to the accepted idea of archaeological documentation as an interpretation, which was pointed out by Tyszczuk (2006) when citing the basic textbook

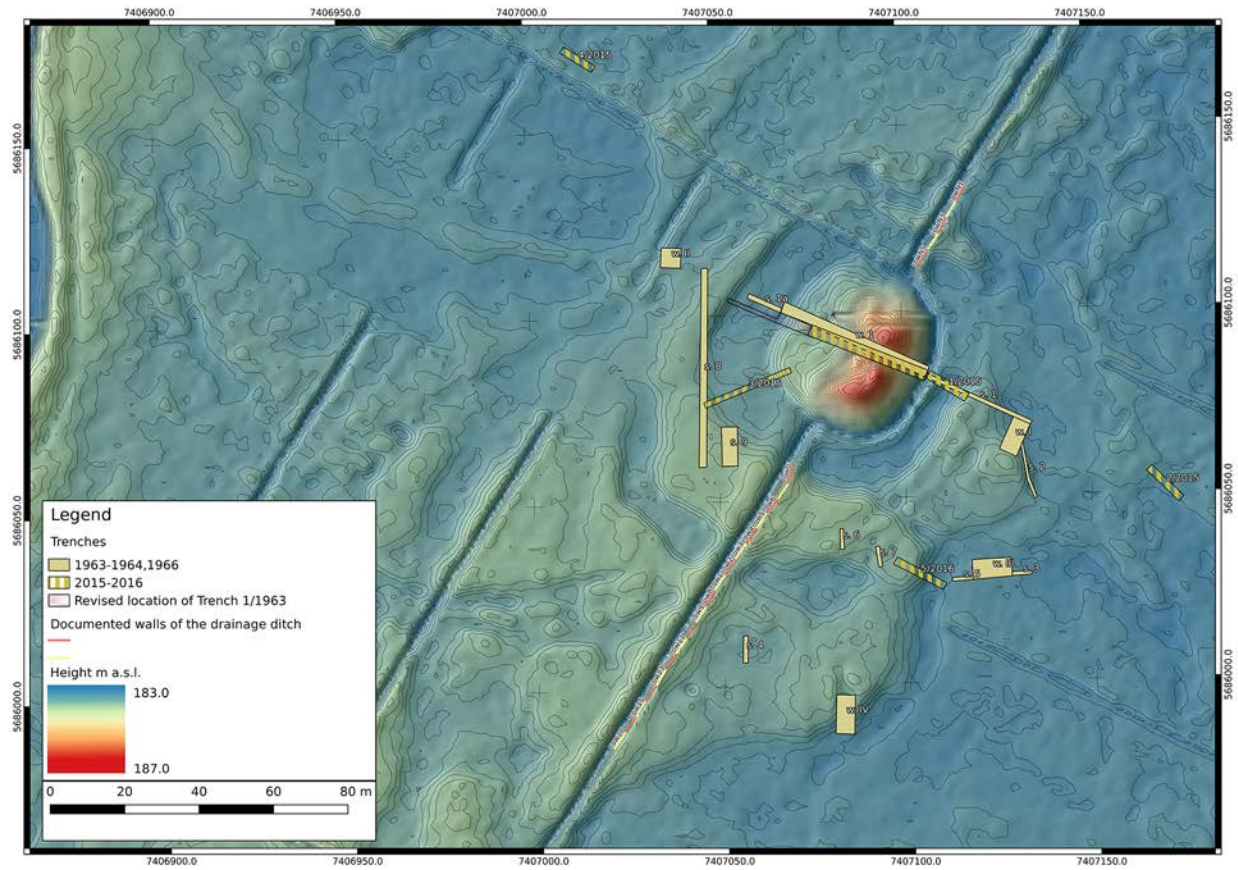

Figure 1. Hill shaded Digital Terrain Model of the Rozprza site with marked trenches (CODGiK, processed by J. Sikora).

of Barker (1993). Furthermore, there is a contradiction in this approach: documentation cannot be interpretation. As Tyszczuk pointed out, contemporary digital methods of archaeological record allow for avoiding any subjective elements in the process of documentation. He also suggested that archaeological documentation should be deprived of any element of interpretation. But we must remember that the very process of exploration already contains elements of interpretation. Archaeologists make decisions in the field, based on their knowledge and experience of both stages of the removal of successive layers. The same can be said about the documentation process. This always involves arbitrary determination of boundaries of layers. The whole process of excavation is, as Hodder pointed out, 'influenced by one's interpretation of what is happening and by what one is finding' (Hodder, 1999, p. 92).

Although archaeological documentation contains an aspect of subjectivity, this factor can be reduced to a minimum with the use of photogrammetric techniques.

The site

The site (51°18'07'' N; 19°40'04'' E; 182-183 m a.s.l.) is situated in Central Poland ca 60 km south of Łódź, in the middle sector of the Luciąża River valley. The settlement complex along with the ring-fort is situated in the central part of the Luciąża River valley floor on the Weichselian terrace remnant which likely adjoins the Holocene floodplain.

According to written sources from the 11th–13th centuries, Rozprza was one of the most important medieval strongholds in Central Poland, beside Łęczyca, Sieradz and Spycimierz (Kamińska, 1953, 1971; Chmielowska, 1975; Sikora, 2009). It is mentioned for the first time in the so-called Mogilno Falsification from 1065 AD. It appears then in the Bull of Gniezno from 1136 AD in the group of important ducal strongholds paying tribute to Archbishops of Gniezno. In the 13th century it was a seat of a castellane — a local ducal official, but in the next century it is mentioned as private property of the Nagodzice noble family.

The site in Rozprza underwent archaeological excavations in 1963–1966 under the supervision of A. Chmielowska from the Museum of Archaeology and Ethnography in Łódź. A series of excavations and test trenches were conducted, aiming to identify the stratigraphy of the stronghold and the adjacent area. As a result, Chmielowska (1966, 1982) distinguished

Figure 2. Excavations in 2016 — wet conditions in the trench (photo by J. Sikora).

four phases of the feature, starting from the 6th up to the 14th century.

Current research started in 2013, and significantly changed the previous knowledge both on the spatial situation of the site and its chronology, which turned out to be much later (from the end of the 10th century). Our works started with a non-invasive survey project, which included analytical field walking, aerial photography, geochemical and geophysical prospection (magnetic gradiometry and earth resistivity survey) along with detailed geological and geomorphological mapping. In 2015 and 2016, excavations were undertaken within five archaeological trenches. They allowed for recording of archaeological features and cultural layers of surviving rampart features and moat fills, and for an identification of palaeochannel fills and subsurface overbank deposits. Additionally, the trench from 1963, which cut through the surviving part of the stronghold's earthwork, was re-opened during the fieldwork in 2015. At the same time, in order to better understand the stratigraphy of the entire terrace remnant on which the settlement developed, the wall of a drainage ditch which went through the site was cleaned and documented. It allowed for obtaining an almost complete section of the settlement area along the NE–SW axis (Figure 1).

As the site is situated in the valley floor, the exploration conditions of part of trenches were extremely wet. In these cases, the work required a permanent operation of the motor water-pump to remove inflowing groundwater (Figure 2). Such working conditions, with lots of wet organic deposits (organic mud, gyttja and peat) posed a significant threat to electronic devices. But it also caused quite a good state of preservation of organic matter, timber constructions, leather and wooden artefacts and dozens of ecofacts (plants macro-remains, bones, fossil Diatoms, Cladocera, Diptera, beetles, molluscs, etc.) which were subject to numerous specialist analyses. These analyses allowed for the identification of human impact on the natural environment and palaeoecological reconstructions of natural changes.

Methods and results

Unlike in the majority of examples of the use of 3D photogrammetry which are known to us, we did not document selected features or trenches only on a certain level of exploration. Instead of this, we decided to document every stage of our work (e.g. Callieri *et al.*, 2011; Berggren *et al.*, 2015). More than 100 models were calculated using 3D photogrammetry, with 8 to 50 photos for each. Such an extensive use of photogrammetry techniques requires the application of specialist hardware. Furthermore, the organisation of work is of crucial significance, as it helped us to fill the afore-mentioned gap between the acquisition of data and preparation of the final model. We decided that it would be absolutely impossible to leave the analysis of the stratigraphy for the post-excavation stage. The objective of documentation and stratigraphic analysis cannot be restricted to the mere appearance (colour and spatial range) of stratigraphic units, but it must also take into consideration their detailed geological characteristics. A developed workflow must therefore include a detailed description and preliminary interpretation of stratigraphic units on-site, in direct contact with them, 'at the trowel's edge' (Berggren *et al.*, 2015; see also Hodder, 1999).

The acquisition of data (i.e. taking photos) was carried out with Sony A57, Nikon D40 and Nikon D5300 cameras. A particularly important feature is a fully articulated LCD screen of cameras, which allows for taking photos with outstretched arms. During the documentation process in Rozprza, it was extremely important to perform a full photographic coverage without using drones or any photographic towers. The width of the trenches (which

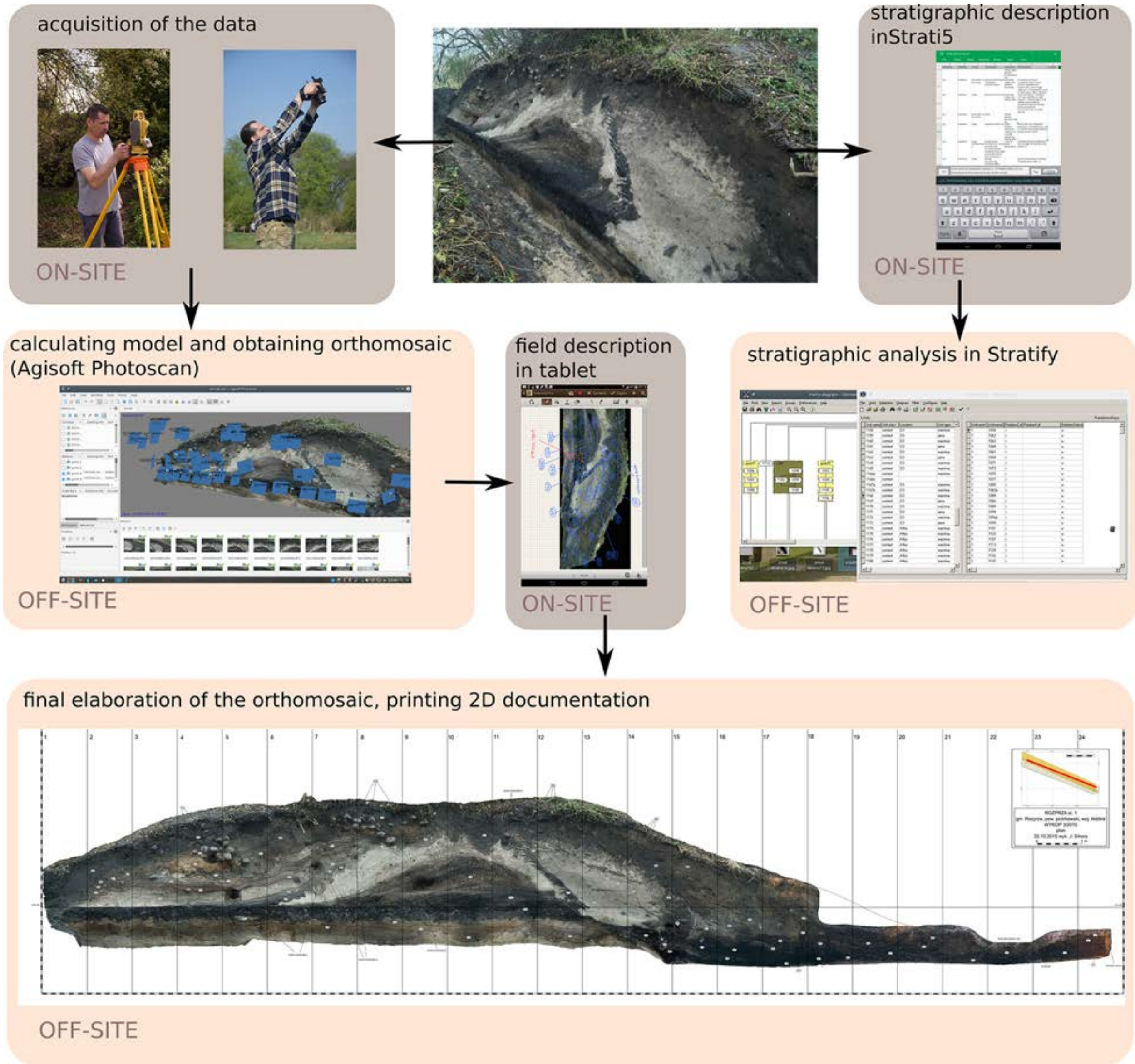

Figure 3. Scheme of the documentation workflow (drawing by J. Sikora).

did not exceed 3 or even 1.5 meters) simplified the process of taking photos. All measurements were done with a Hi-Target V30 GPS RTK system with an Android OS-based iHand controller. The use of Android (or any modern OS)-based devices allows to use a whole range of useful additional applications, including a cloud file storage application, which simplifies communication between devices. We also used a TopCon total station for measurements in difficult terrain, such as the embankment of the stronghold, which was covered with trees and deep trenches. For calculating 3D models and later processing in the GIS environment as well in graphic software, a Lenovo U430 Touch laptop (or ultrabook, as the seller wanted to call it) was used (with Intel Core i7 processor, 8 GB RAM, and NVIDIA GeForce GT730M 2 GB graphics). As a supplement, a 10 inch Android tablet with a pen-digitiser was used (Samsung Galaxy Note 10.1). The last tool, a simple and not up-to-date toy, was an important device in the entire process of documentation, as it allowed us to completely abandon any form of paper documentation.

The use of the tablet in the digital workflow associated with the field survey in archaeology is not a new idea. Similar proposals have already appeared and been discussed in scholarship. They usually result from the application of specialised rugged (but usually rather expensive) laptops or tablets (Searcy and Ure, 2008; Motz and Carrier, 2013). But as the new generation of lightweight and relatively inexpensive tablets is available, these devices become more and more popular as a tool for archaeological documentation experiments. In most cases it is the Apple iPad with a customized FileMaker Database Management System

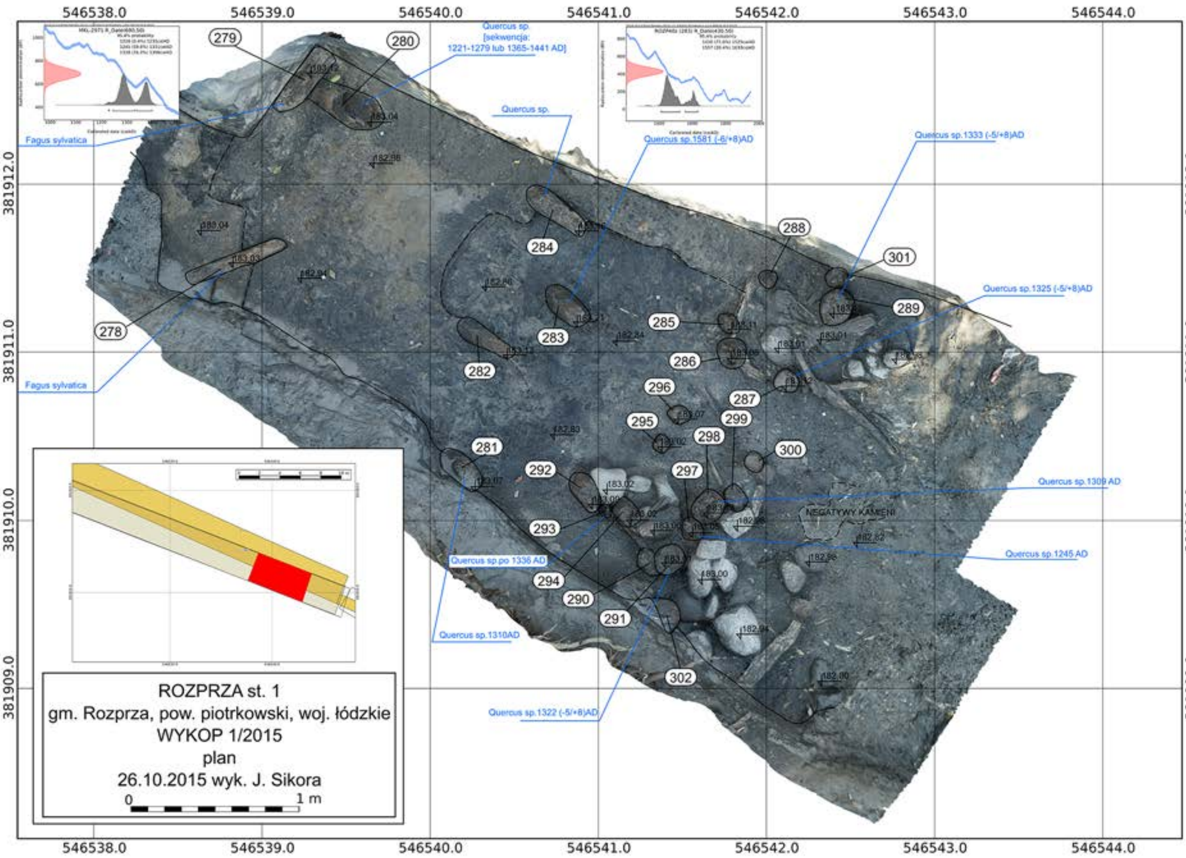

Figure 4. Example of two-dimensional final documentation – re-excavated Trench 1/1963 (processed by J. Sikora).

and a vector drawing application, such as TouchDraw or iDraw/Autodesk Graphic (paperlessarchaeology.com, n.d.; Wallrodt and Ellis, 2011; Jackson *et al*., 2016).

The use of the tablet in the field involves a number of drawbacks. The surface of the screen of the tablet is usually smaller than an A4 or A3 sheet of paper used for hand-drawn documentation. It does not matter in the case of descriptive documentation but gains importance in the case of drawings. Using a tablet as a replacement of a paper sheet was not efficient in the field. An attempt at preparing 2D vector drawing on the tablet, which is known from the literature, resulted in many problems associated with the need to handle the software. Most importantly, it took much more time than traditional drawing on paper. In addition it required further processing on a desktop computer. In our approach, any field drawings were replaced by 3D documentation in Agisoft Photoscan. It was only supplemented with supporting sketches drawn on the tablet and was later used to prepare final graphics. We also found several advantages of tablet over laptop in fieldwork: no hinges (less susceptible to mechanical damages), relatively cheap (loss in the mud will be less painful) and accurate enough for taking notes with the use of a stylus/pen.

The whole documentation workflow includes several steps (Figure 3):

Step 1 (on site) — taking photos and measurements for photogrammetry, initial description of deposits and other stratigraphic units. For field description we have used a Strati5 application (Sikora *et al*., 2016), which works under the majority of spreadsheet software, including Microsoft Excel, Open/Libre Office, WPS Office, and under the majority of operating systems (Windows, GNU/Linux, MacOSX, iOS, and Android). Strati5 cooperates with the popular Stratify software (Herzog, 2005), which helps in stratigraphic analysis and in creation of the Harris Matrix.

Step 2 (off site) — calculating 3D models in Agisoft Photoscan and the preparation of georeferenced orthophotos.

Step 3 (off site) — processing of orthophotos in QGIS. Plans become part of our Archaeological Information Systems (AIS), sections are imported to QGIS only for setting a georeferenced grid, necessary in further work.

Step 4 (on site) — a copy of the orthophoto (plan or section) is imported to the tablet, delineated with the use of a graphic application and described in Strati5 directly in the field.

Step 5 (off site) — final processing of orthophotos with the use of raster and vector software (Gimp, Inkscape — open source applications).

This workflow organisation requires a break in the exploration in order to carry out Steps 2 and 3. Usually the processing of models and orthophotos takes a few hours. In this time the exploration team leaves a given trench or section and is moved to another location, while the documentation team works on calculating 3D models and orthophotos. Everything is a matter of a proper organisation of work and team management. There are of course certain situations when it is not possible to take a break in a trench or section which is to be documented. In such circumstances a modification of the workflow is possible:

Step 1 (on site) — does not change — it is still acquisition of photos and measurements in the field.

Step 2 (on site) — the documented stratigraphy unit (or units) is additionally photographed with the use of a tablet built-in camera. The photos are described using a graphical-note taking application and Strati5.

Step 3 (off site) — a 3D model is calculated and an orthophoto is prepared using Agisoft Photoscan. Obtained orthophotos are further processed in QGIS and graphic software.

In both cases the result is a 3D model for further advanced applications, a complete Archaeological Information System, and above all, a 2D graphic plan or section of a stratigraphic unit (or a set of units), ready to be printed, as required by the Office of Monument Protection (Figure 4).

The low cost of these solutions was particularly important. Within a limited budget, we wanted to allocate more funds for extensive specialist analyses and execution of more radiocarbon and dendrochronological data sets than for shiny and up-to-date equipment which may become rapidly outdated in a few years. Other limitations were external conditions, such as:

- Poor GSM Internet coverage which did not allow for the use of external computers for calculations in point clouds,
- The aforementioned heavy terrain conditions which did not allow for the use of laptops directly on-site, due to wet and muddy environment.

Conclusion

The main goal of the discussed documentation workflow was, on the one hand to meet requirements of heritage institutions in Poland which revere two-dimensional paper documentation, and on the other hand to demonstrate possibilities offered by contemporary digital techniques for an affordable price. We found several advantages of such an approach: first of all, it saves time needed for field data acquisition. The sum of steps is reduced only to establishing reference points, measurements of these points with a total station or an RTK GPS, and taking a series of photos. The next on-site step is to describe the documented features. This whole set of activities is much faster than traditional drawing. But nothing is for free. Unfortunately, it significantly increases the post-excavation off-site stage. Thus the fast acquisition stage seems to be one of the strongest points of the proposed attitude. It could be crucial in cases of changing and unfavourable weather conditions or unstable trench walls (in wetland archaeology, there is always a danger of washing out the walls and the destruction of profiles). The most important advantage is that we can obtain very accurate documentation (much more precise than traditional hand–drawings), and even simplified 2D orthophotographic documentation with the use of raster graphic software and the QGIS georeferencing module.

The documentation obtained with the discussed workflow is not only accurate, but could be also supplemented with an interpretative layer. An important part of the process is sketches prepared with the tablet. They contain interpretation of borders of stratigraphic units, numbering and any notes and comments which seem to be important (similar actions as part of the excavation process in Çatalhöyük are discussed in Berggren *et al.*, 2015). In addition, the interpretation is included in the description of stratigraphic units. Interpretation is a multi-stage process, but the first step is carried out in the field, 'at the trowel's edge', in direct contact with documented features. The final form of graphic documentation, apart from clean orthophotos, can also contain an extensive interpretative layer. Besides all this, it is very attractive visually and its potential for further GIS analyses has not been fully recognised yet. We believe that the discussed documentation workflow is a reasonable choice, which takes into account financial factors, relative ease of use, external factors such as Internet access and above all an appropriate level of accuracy and fulfilment of requirements posed by heritage services. As we are fully aware that these requirements could vary in different countries and provinces, we rather encourage not so much to reproduce the discussed methods, but to develop them in a creative manner.

Acknowledgements

The research project in Rozprza has been funded by grants from the National Science Centre, decision No. "DEC-2013/11/B/HS3/03785" and from the Ministry of Culture and National Heritage, decision No. 01619/13. We are indebted to P. Wroniecki and G. Żabiński for linguistic corrections of the manuscript.

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Mieko Matsumoto and Espen Uleberg (eds) 2018. ***CAA2016: Oceans of Data***
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
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Supercomputing at the Trench Edge: Expediting Image Based 3D Recoding

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Abstract

Image-based 3D reconstruction with Structure From Motion (SFM) techniques are increasingly used for documenting archaeological excavations, providing an inexpensive means of recording detailed spatial and radiometric data. However, these methods are computationally intensive. Processing can take hours. This is problematic, as excavation is a destructive practice, contingent on validating and interpreting the record in the field. Therefore, rapidly processing the models and making them available to archaeologists as they excavate is vital.

We demonstrate how 3D reconstruction can be expedited. By processing the images over a mobile connection to a High Performance Computing (HPC) cluster we can increase the computational power available on site. Then, we examine the effect different parameters have on processing speed and quality of the finished model. Last, data transfer and processing time can be further optimised by constraining image size appropriate to the scale of the objects being recorded.

Keywords: image based 3D reconstruction, high performance computing, archaeological fieldwork, recording, structure from motion

Introduction

Over the past decade, developments in image-based 3D reconstruction have led to it being increasingly utilised for archaeological documentation. While photogrammetric techniques have been used for recording archaeological information since the early 20th century, recent developments in hardware and software have been transformative. There are several reasons for this. Digital cameras with fixed imaging arrays have negated the need for specialised survey cameras (Linder, 2009; Läbe and Förstner, 2004). The ever increasing computational power available in affordable consumer grade hardware has made processing and display of rich 3D data sets possible, in particular the availability of Graphics Processor Units (GPUs) for parallel processing (Verhoeven, 2011; Munshi *et al.*, 2011). The development of computer vision algorithms such as SURF (Speeded Up Robust Features) (Bay *et al.*, 2008) and SIFT (Scale Invariant Feature Transform) (Lowe, 1999) for feature matching, robust bundle adjustment algorithms and their integration in user-friendly SFM (Structure From Motion) and multi-view stereo software packages have meant that the process of photogrammetric measurement is largely automated, and requires little specialist knowledge (Green *et al.*, 2014; Lo Brutto and Meli, 2012; Kersten and Lindstaedt, 2012; Olson and Caraher, 2015).

These developments have made the technology cheaply and easily accessible, and the accurate, richly detailed spatial and radiometric measurements produced by these methods have led to these techniques being widely adopted by archaeologists for documenting excavations (for example Callieri *et al.*, 2011; Forte *et al.*, 2012; De Reu *et al.*, 2014; Roosevelt *et al.*, 2015). Excavation is an intrinsically destructive process, meaning that the entities being recorded often only exist in the record (Lucas, 2000; De Reu *et al.*, 2013). This means that being able to validate and interpret that record in the field, while the entity still exists, is essential. However, the computationally intensive nature of image-based 3D reconstruction entails long processing times, meaning that often models are generated after the excavation, making validation of the models difficult.

Several approaches to resolving this have been attempted. Performing the reconstruction using reduced quality settings can be used to expedite production of an interim model for use in the field (e.g. Kjellman, 2012; De Reu *et al.*, 2014; Taylor *et al.*, 2015, p. 195; Ahrens and Borvik, 2016, p. 16), with the possibility of making a higher-quality model afterwards for post-excavation analyses and archiving. Alternatively, it is possible to let the field computer run overnight so the finished model is available the next day (e.g. De Reu *et al.*, 2014; Spence Morrow *et al.*, 2014). While these strategies work, they have problems. Producing lower-resolution models may not deliver information of the required accuracy and resolution, and may hinder further analyses. To generate a low and a high resolution model necessitates double handling the processing and introduces complexity in the documentation process in data management terms. Finally, starting the modelling processes at the end of the working day and letting the computer run overnight may delay excavation work, and is not feasible where many models need to be produced simultaneously.

In this paper, we investigate ways in which 3D reconstruction can be expedited to enable archaeologists on excavations to produce and utilise finished models on site within reasonable time frames. The first approach investigated is using a 4G mobile internet connection to connect to the DEIC Abacus 2.0 High Performance Computing (HPC) cluster at the University of Southern Denmark as part of the HPC Archaeology project. Image based 3D reconstruction, in particular the feature matching and bundle adjustment stages, is an embarrassingly parallelisable problem (Foster, 1995; Wang *et al*., 1996). By increasing the number of CPU and GPU cores available, the time taken for processing the models can be drastically decreased. While image reconstruction using network processing has been widely adopted by domains outside archaeology, such as in the film and game industries (for example Failes, 2015), these tend to use dedicated hardware clusters. These are outside the financial reach of many archaeological institutions, but access to HPC clusters by research institutions is affordable. Online and cloud based processing services are also available.

The second approach is to examine the extent to which image resolution and processing parameters used can be optimised. By moderating these we can reduce both the amount of data transferred and the overall processing time. While ideally preservation by record should always record at the best attainable resolution, much of this information is potentially redundant. For example, for recording the extents of archaeological units to sub-centimetre resolution is unnecessary, whereas recording faint inscriptions requires a much higher resolution. By taking a pragmatic approach, incorporating an understanding of the intended purpose of the model, the level of detail of the phenomena being recorded, and the resolution required, we can optimise these parameters effectively without compromising the utility of the finished model.

Methodology

Existing workflow

The existing workflow used by Aarhus University and Moesgaard Museum for 3D reconstruction is to download the images and total station measurements of the coded targets used for automated geo-referencing on to the on-site laptop. These are then transferred via a 3G / 4G mobile broadband modem to the Unit of Archaeological IT, who perform the 3D reconstruction on a dedicated workstation. When the reconstruction is complete, the finished model and outputs such as orthophotos and DEMs are sent back to site.

Proposed workflow

Using this workflow provides the 3D data to the excavation quickly, often within a few hours. However, in periods of high demand it becomes difficult to keep up. For example, where there are several excavations running concurrently or there are many large models to be run. Using the mobile internet connection to directly process the 3D reconstructions on the HPC offers the potential to both speed up the processing and provide capacity to process many models concurrently. Figure 1 outlines the proposed workflow for using the HPC on the excavations.

Testing

To test the feasibility of this workflow we compared the performance of the HPC nodes and the local workstation to examine the extent to which reconstruction could be speeded up, henceforth referred to as *performance testing.* To further investigate how performance could be improved we examined the trade-offs between image resolution, performance and model resolution, henceforth referred to as *resolution testing,* and the effects of changing the processing parameters, referred to as *parameter testing.*

The practicality of connecting to the HPC using the 4G modem was also tested during 2015 by visiting the active excavation at Skødstrup, where it was possible to obtain a reliable 4G internet connection with a 15Mbps download speed and a 6Mbps upload speed.

Test data sets

The study ran benchmark tests on two data sets (Table 1). The first, comprising 29 images is from a rescue excavation undertaken by Moesgaard Museum at Borggade in Aarhus was used for parameter and resolution testing, and for comparing the performance of the local computer and HPC nodes. The second, larger, data set, comprising 183 images from a research excavation of an Iron Age mass grave at Alken Enge undertaken by Aarhus University was used for testing performance of multiple HPC GPU nodes.

Hardware

Two distinct hardware systems were used for performance testing and benchmarking for this study

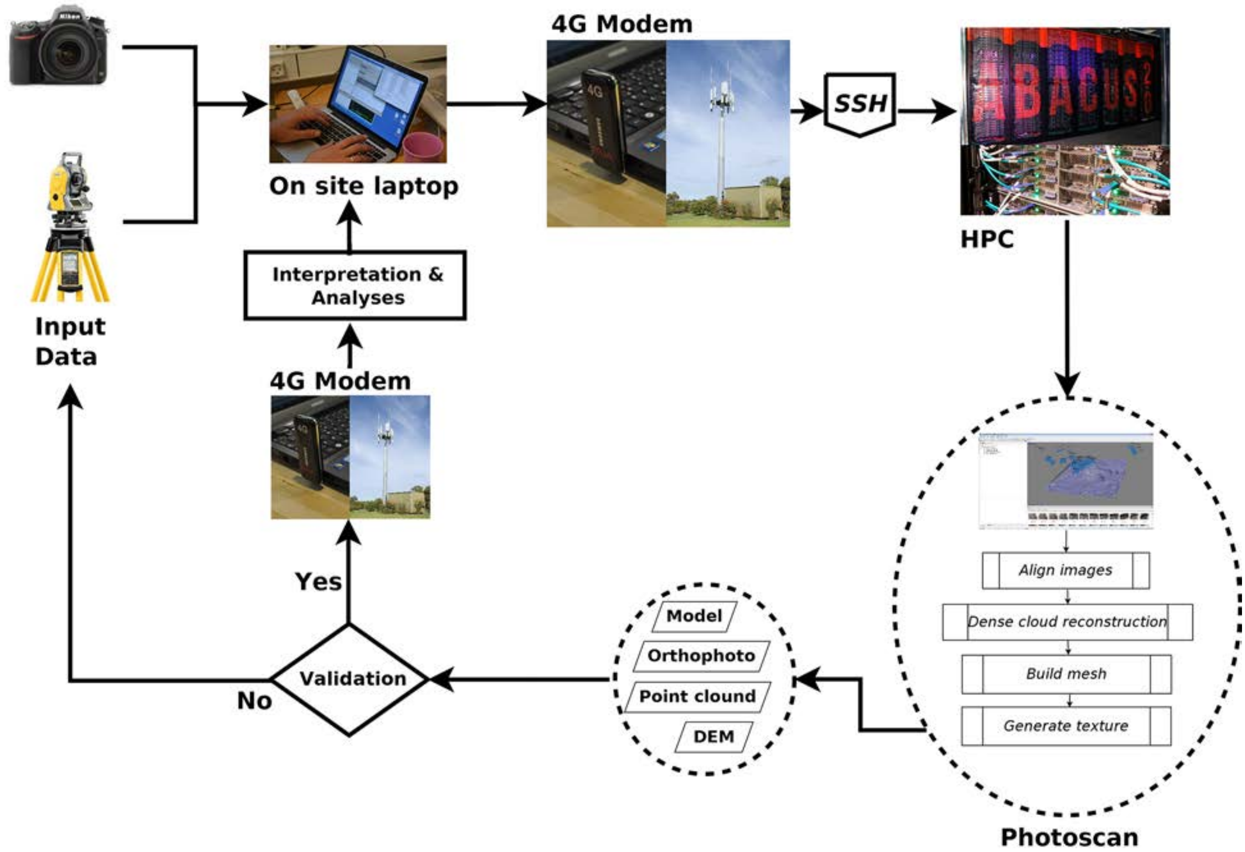

Figure 1. Input data in the form of photographs and total station measurements are downloaded to the on-site laptop. These data are then transferred to the HPC using the SFTP protocol and processed using AgiSoft PhotoScan using VNC and SSH connections. Data are checked on over these connections, and if satisfactory downloaded for further analysis and interpretation.

Data set	Camera	Focal length (mm)	Image resolution (Pixels)	Number of images
Borgade	Nikon D700	24mm (84º FOV)	4256 × 2832	29
Alken Enge	Nikon D7000	16mm (83 º FOV)	4928 x 3264	183

Table 1. Test data sets.

Computer	Processor	RAM	GPU
Workstation Windows 8.1	Intel i7-5960X: 8 cores @ 3 GHz 16 Threads	64 GB	2 x nVidia Geforce GTX 980: 4096 cores @ 1126 MHz 4 GB memory
2 Abacus GPU node CentOS Linux 7	2 x Intel E5-2680v3: 24 cores @ 2.5 GHz 48 Threads	64GB	2 x nVidia K40: 5760 cores @ 745 MHz 24 GB memory

Table 2. Computer hardware used for testing.

(Table 2). The first is a high end gaming computer with dual graphics cards, of the type generally recommended for image based 3D reconstruction. The second were the GPU nodes on the HPC cluster. There are 72 GPU nodes in total, connected by a 56 Gbit/s network in a 3D Torus configuration. Jobs on the HPC are managed using the SLURM (Simple Linux Utility for Resource Management) workload manager. As of the 1st of July 2016 access to the HPC cluster costs DKK 2.65 (€ 0.36) per node per hour (DeIC National HPC Centre, 2016).

Software

The Agisoft PhotoScan 1.12 (Agisoft LLC, 2016) software package was used for testing because it runs on Linux and supports network processing, and thus can be used on the HPC. Additionally it provides a well-documented Application Programming Interface (API) in the Python programming language, enabling the automated testing of parameters (Agisoft LLC, 2014). However, due to constraints imposed by the software it is not currently possible to use the Python API in conjunction with networked processing on multiple HPC nodes.

The PhotoScan network processing architecture uses one machine designated as a server that delegates work to a number of processing nodes connected to it, with a client running the Photoscan Graphical User Interface (GUI) controlling the PhotoScan workflow (Agisoft LLC, 2015). Due to networking latency constraints the client was run on one of the HPC nodes, rather than locally, using a Virtual Network Computing (VNC) connection over Secure Shell (SSH). VNC enables use of GUI over the network with less lag than X-forwarding over SSH. The client and server were run on the same node, with each processing node being run using an SSH connection. The client, server and each processing node require a separate software license. The project has 20 licences available.

Performance testing

Performance testing was conducted using both the Borggade and Alken Enge data sets, as it was apparent that the Borggade data set was not large enough to test a large number of nodes on the HPC. Because it is not possible to use the Python API for multi-node processing the testing was performed manually using the Photoscan GUI. Models were run on High Accuracy for image alignment, High Quality for the dense cloud reconstruction and High Face Count for model generation.

Resolution and parameter testing

To test resolution and processing parameters the Python API was used to automate performance testing, using customisable JSON configuration files and saving detailed information about each processing stage. Results were assessed using *model resolution* parameter from the model metadata, which gives the mean density of vertices in the reconstructed mesh. Due to the limitations of the Python API discussed above these tests were run on a single GPU node.

For resolution testing, the images were resized using a Python script to resize each image while preserving the original sensor ratio. This produced images with 13 different resolutions. For parameter testing three settings with the largest impact on processing time were selected (Agisoft LLC, 2016). These were alignment accuracy, dense cloud quality and model face count.

Results

Performance testing

Using the HPC provided a considerable reduction in the amount of time required to compute a finished model over using the local workstation, even on a single node. Predictably, adding more nodes reduces the processing time (see Figure 2). However, the results indicate the relationship between the number of nodes and the time taken is non-linear. For example, for the Borgade data set there is a substantial time saving between using one and two nodes, but there is little to be gained using more than this.

On the larger Alken Enge data set (Figure 3) there is a large gain using 6 over 4 nodes, but after this the returns also diminish, with 12 nodes producing a result that is only 21% faster than 6. This indicates that performance is being limited by Amdahl's law (Amdahl 1967), which asserts that the theoretical speedup obtained by parallel processing is limited by the extent to which the problem can be parallelised. The algorithms used by PhotoScan are not documented, so it is difficult to ascertain where any bottlenecks in the reconstruction workflow are located. The greatest gains are made in the alignment and dense cloud reconstruction stages. Additionally, the gains for each additional node increase with the number of images. This indicates that the number of images dictates how the work is divided among the processing nodes, with operations on individual images or pairs of images such as feature detection and matching, bundle adjustment and depth mapping showing the greatest performance gain. There is little benefit in performance using multiple nodes for mesh and texture generation.

Parameter testing

Dense cloud quality has the greatest effect on processing time and model resolution (Figure 4). Using the highest quality setting substantially increases the amount of time required for model generation, producing a model resolution of ca 2.8 mm. Using the high quality setting halves the model resolution and reduces processing time five-fold. Further reducing the dense cloud quality reduces the model to over a centimetre, but total processing time is under 5 minutes. However, it is worth noting that the 3D resolution of vertices in the model is independent of the resolution of the mapped textures, meaning that high 3D resolution is only necessary where intricate morphological structures need to be recorded. Often this is not the case for on-site archaeological recording, where the nature of the excavation process means we are often recording surfaces rather than complex structures.

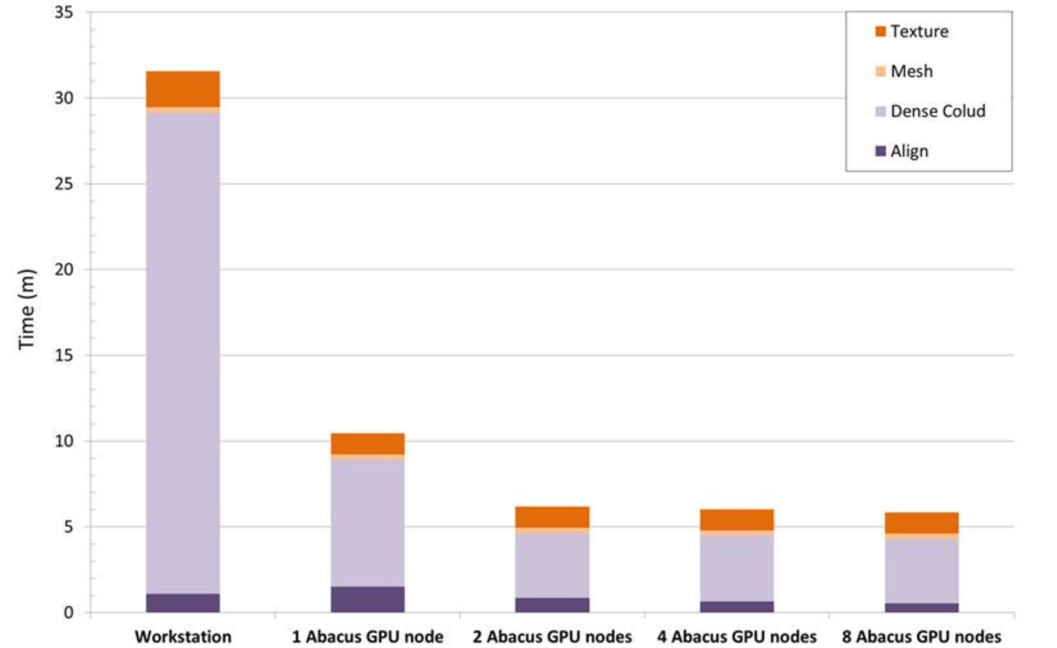

Figure 2. Performance benchmarks comparing the local work station and HPC nodes using the Borggade data set.

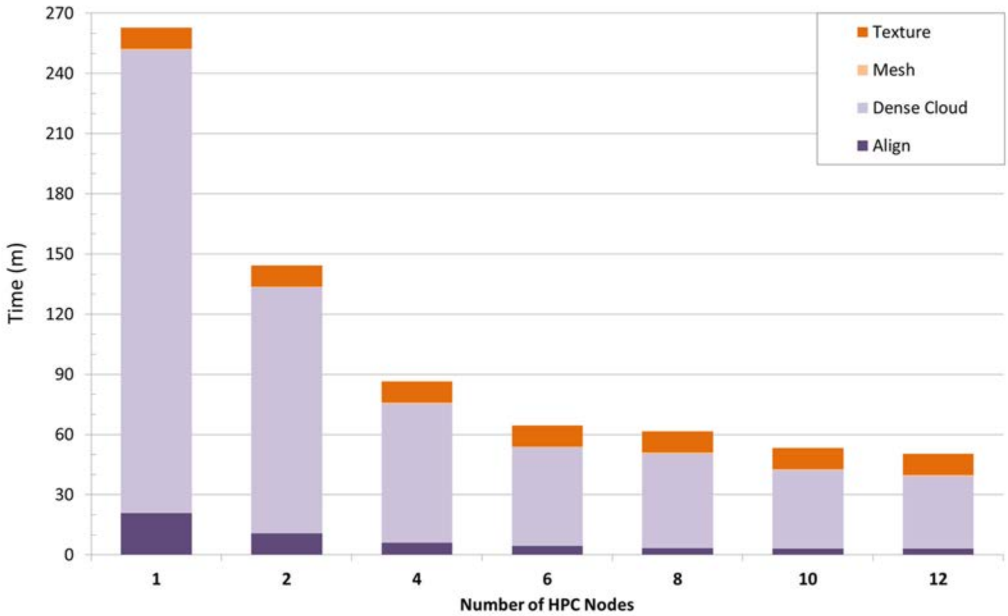

Figure 3. Performance benchmarks on multiple HPC nodes with the Alken Enge data set.

Alignment accuracy and model face count do not have a major impact on processing time or model resolution.

Image resolution

Reducing the image size has two benefits. First, it reduces the amount of bandwidth and thus time required to upload the images for processing over the mobile network (Figure 6). Second, it further reduces processing time with only a minor reduction in model resolution (Figure 5). For example, halving the image resolution to a nominal 6 megapixels also halves the overall processing time, while reducing the model resolution from 4 mm to 6 mm. However, reducing the image size will effect the resolution of the mapped

Figure 4. Parameter testing results from a single HPC node.

textures in the finished model, so it is imperative that the choice of image resolution used is appropriate to the phenomena being recorded and the intended purpose of the model. Table 3 details conventional scales used for archaeological recording, and suggests appropriate model resolutions. Figure 7 shows the idealised relationship between sensor resolution, distance from the subject and spatial resolution and area covered for a typical wide angle lens on a DSLR. Selecting the optimal sensor resolution is a trade-off between the required spatial resolution, the distance achievable from the camera to the subject, and the number of images required to cover the subject at that resolution.

Discussion

There are a number of limitations to this work. The first of these is connectivity. This solution is only tenable if the size of the upload relative to the bandwidth of

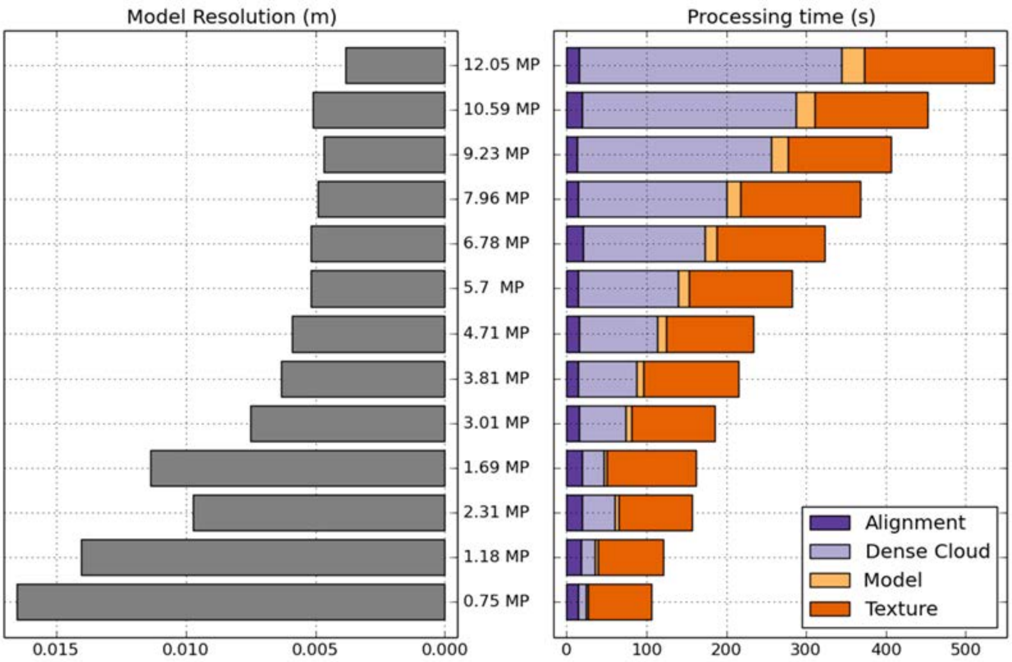

Figure 5. Performance and model resolution effects of changing image resolution.

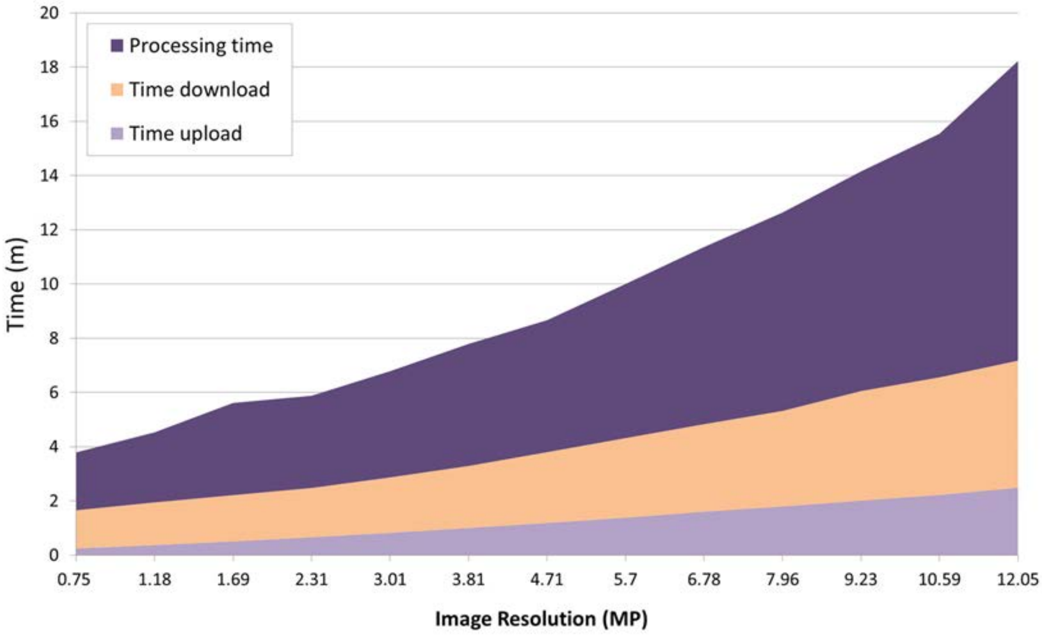

Figure 6. Total processing time, including time to upload the images and download the finished model on a 6Mbps internet connection at different image resolutions.

the connection are commensurate. If the time taken to transfer the images and download the finished model exceeds the gains made from processing on the HPC there is little advantage to using it. This means that to be practical a 3G HSDPA or 4G internet connection is required. Denmark is a comparatively flat country, with excellent mobile broadband coverage. Even so, it may not always be possible to obtain a connection on site away from urban centres. This is especially pertinent for other countries with less comprehensive network coverage in remote areas. Mobile satellite broadband

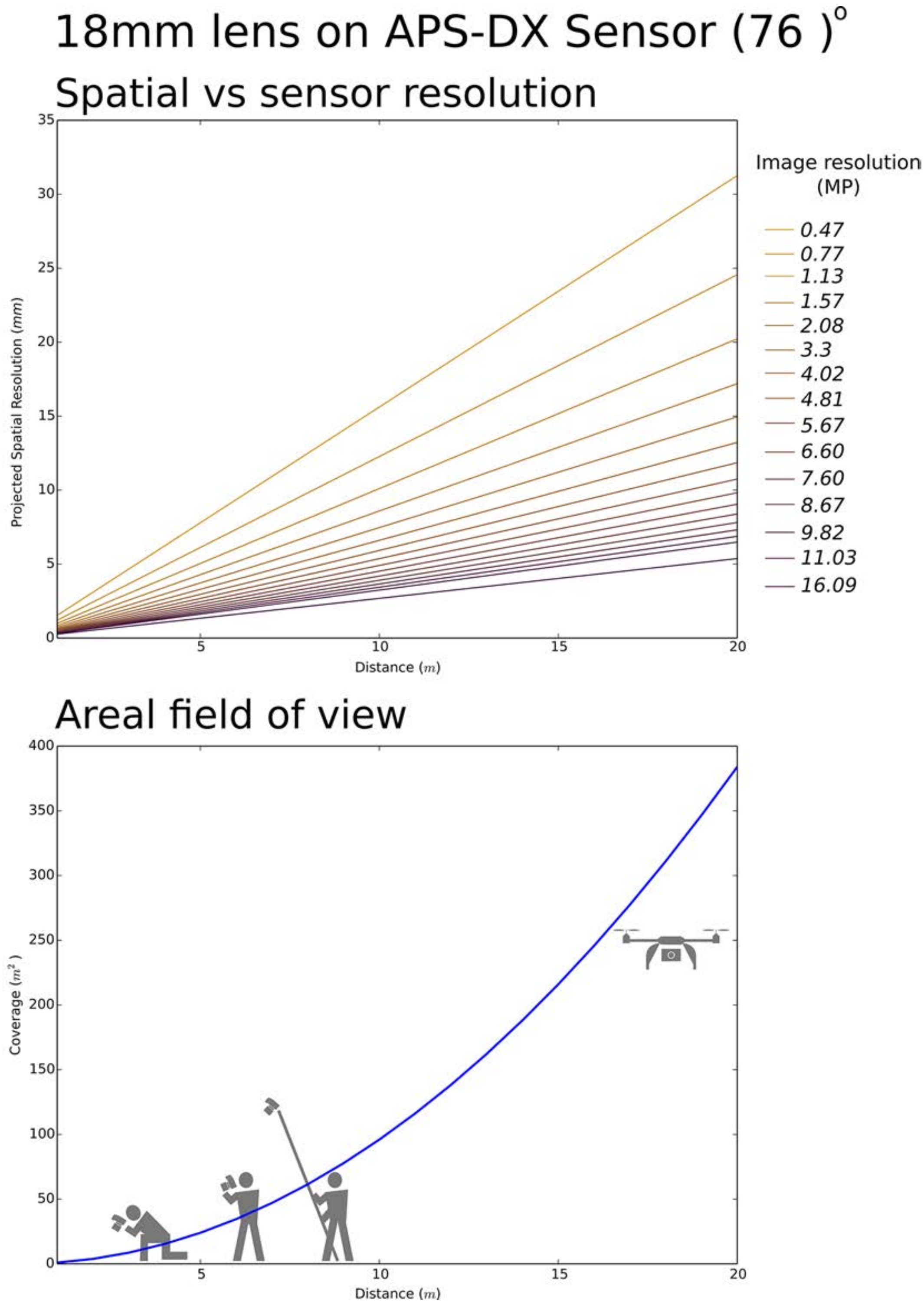

Figure 7. The effects of changing image resolution and distance on spatial resolution and image coverage.

is expensive, slow, and with high latency, potentially negating the benefits of processing on the HPC.

Cost is a further limitation on the utility of these approaches. While access to the HPC is comparatively cheap, the requirement for multiple software licences means that this approach is not feasible for smaller organisations, especially if commercial licences are required (Green *et al.*, 2014). Additionally, the constrained Python API and requirement to run a GUI imposed by the PhotoScan software package make implementing a fully automated workflow difficult,

Subject	Drawing Scale	Suggested model resolution	Suggested photo resolution	Processing Time	Transfer time
Site plan	1:50	10mm	4MP	30%	30%
Context plan	1:20	5mm	6MP	60%	75%
Profile / Detail plan / Skeleton	1:10	<1mm	12MP	100%	100%

Table 3. Typical scales used for archaeological drawing and suggestions for suitable equivalent model resolutions, input image resolutions and time savings, assuming a 2.5 m working distance.

necessitating manual intervention to set up and process the model. This work is also technical, requiring specialised knowledge to set up the SSH connections to the processing network. Ideally this should be fully automated, requiring little or no intervention from the end user on site beyond uploading the images and stating the requirements of the finished model. Open source libraries such as PMVS2/CMVS (Furukawa *et al*., 2010; Furukawa and Ponce, 2010), Bundler (Snavely *et al*., 2006), Theia (Sweeney *et al*., 2015), MicMac (Deseilligny and Clery, 2011) and OpenCV (Pulli *et al*., 2012; Marengoni and Stringhini, 2011) could be used to develop automated workflows for use with HPC clusters at much lower cost, however this would require sizable investment in development of software to obtain a software stack with functionality equivalent to PhotoScan, and likely without conveniences such as automatic geo-referencing, DEM and orthophoto production.

Another issue is the availability of the HPC itself. The service is in high demand, with many other users accessing it. This means that during busy periods it is not possible to obtain access. This could be avoided by purchasing time on the cluster at predetermined times, or even buying dedicated nodes. The combination of these approaches may be the best solution, as a dedicated node could be always available, but periods of high demand could be met by purchasing time on additional nodes as required.

While this paper demonstrates some of the principles governing image coverage, resolution and processing parameters, it is impossible to make comprehensive recommendations for image acquisition and reconstruction settings, as these depend upon wide range of external factors. These include the morphological and textural complexity of the object, the photographic equipment available, constraints in photographing it, and the purpose of the finished model.

Optimising image resolution and processing parameters requires a solid grounding in both optical principles and the functions of the software. Communicating this knowledge to the archaeologists acquiring images on site is essential. This could be addressed by the provision of simple software calculators to determine the best image resolution and processing parameters. A simplified example of such a calculator developed for this work can be found here: https://github.com/dav-stott/CoverageCalc/blob/master/CovCalc.py.

Conclusions

We have demonstrated that it is possible to substantively decrease the time required to produce models on site, using both the increased computational power of the HPC and by optimising the image and processing parameters. For example, by using 12 HPC nodes instead of one to run the Alken Enge data set we can reduce the time taken to run the model at full resolution and high quality settings from over 3 hours to under 50 minutes. By reducing the image resolution and using the right processing settings we can reduce this further. This makes the use of the finished model in the field by the archaeologist in the trench feasible, and allows for field validation and interpretation without long waits.

However, exploiting this for wider use needs further development. The archaeologists on site need to be able to use it with a minimum of specialist knowledge. This requires improving the ease of setting up the processing network, and determining the optimal image resolutions and processing parameters. The former necessitates further work with automating initialisation of SSH connections to the HPC nodes and setting up the PhotoScan network processing stack. The latter requires development of software tools for use on site to set processing parameters, determine appropriate image resolutions and resize them before uploading to the HPC. This can also be largely automated on the client side, with the user only needing to supply the model resolution and the distance to the subject.

Acknowledgements

We thank the Faculty of Arts at the University of Aarhus for providing the funds for software licenses, and the DeIC for seed-money financing CPU-time on Abacus 2.0. This work would also not have been possible without technical support from Jens Svalgaard Kohrt at the DeIC National HPC centre at the University of Southern Denmark.

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Semi-Automatic Mapping of Charcoal Kilns from Airborne Laser Scanning Data Using Deep Learning

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Abstract

This paper proposes the use of deep learning for semi-automatic mapping of charcoal kilns from airborne laser scanning data. A deep convolutional neural network (CNN) was first pre-trained on 1.2 million photographs in order for the network to learn general high-level image features. The second to last CNN layer was input to a linear support vector machine, which was trained from CNN features obtained from 375 charcoal kiln locations and 10,000 other locations.

In a 3 km × 3 km test area, the automatic method identified 363 of 419 verified charcoal kilns, while 56 were missed. Nine previously overlooked, possible charcoal kilns were also found. The number of false positives was 220.

The proposed method, based on deep learning, is better than our previous attempts at semi-automatic charcoal kiln detection based on traditional pattern recognition methods. The new method detects more true charcoal kilns and has a manageable number of false positives.

Keywords: convolutional neural network, support vector machine, archaeological mapping, LiDAR, digital terrain model

Introduction

Automatic detection methods, based on traditional pattern recognition, have been applied in a number of cultural heritage mapping projects in Norway for the past eight years (Trier *et al.*, 2009, 2015a, 2015b; Trier and Pilø, 2012, 2015). Automatic detection of pits and heaps have been combined with visual interpretation of the Airborne Laser Scanning (ALS) data for the mapping of deer hunting systems, iron production sites, grave mounds and charcoal kilns.

However, the performance of these automatic detection methods varies substantially between ALS datasets. For the mapping of deer hunting systems on flat gravel and sand sediment deposits (Trier and Pilø, 2012), the automatic detection results were almost perfect. However, many false positives appeared in the terrain outside of these sediment deposits. This could be explained by other pit-like landscape structures, such as parts of river courses, spaces between boulders, and modern terrain modifications. However, these were easy to spot during visual inspection, and the number of missed individual pitfall traps was still low.

For the mapping of grave mounds (Trier *et al.*, 2015b), the automatic method produced a large number of false detections, reducing the usefulness of the semi-automatic approach. The mound structure is a very common natural terrain structure, and the grave mounds are less distinct in shape than the pitfall traps. Still, applying automatic mound detection on an entire municipality did lead to a new discovery of an Iron Age grave field with more than 15 individual mounds. Automatic mound detection also proved to be useful for a detailed re-mapping of Norway's largest Iron Age graveyard, which contains almost 1000 individual graves (Trier *et al.*, 2015a).

Combined pit and mound detection has been applied to the mapping of more than 1000 charcoal kilns that were used 350-200 years ago by Lesja Iron Works, Oppland County, Norway (Trier *et al.*, 2015a). The majority of charcoal kilns were indirectly detected as either pits on the circumference, a central mound, or both. However, kilns with a flat interior and a shallow ditch along the circumference were often missed by the automatic detection method.

Schneider *et al.* (2015) recently attempted automatic detection of charcoal kilns in a large kiln field near Cottbus, Germany. These kilns have a somewhat different topographical expression than the kilns from Lesja, but many of the challenges in applying automatic detection are similar, e.g. the number of false detections.

The degree of success of automatic detection seems to depend on two factors: (1) the density of ALS ground hits on the cultural heritage structures being sought, and (2) to what extent these structures stand out from natural terrain structures. The first factor may, to some extent, be improved by using a higher number of ALS pulses per square meter. The second factor is difficult to change, and also highlights another challenge: how to make a general automatic method that is applicable in all types of terrain within a country.

The mixed experience with traditional pattern recognition for semi-automatic mapping of cultural heritage led us to consider *deep learning* as an alternative approach. The main principle is that an object classifier has been trained on a large image database. The object classifier is then tailored to a specific task by using a modest number of images of true and false examples of the specific objects sought. In this paper, we are evaluating the effectiveness of using deep learning in the detailed mapping of charcoal kilns at Lesja Iron Works, and comparing the results with the previous mapping, in which traditional pattern recognition was used to aid visual inspection and field verification.

The 17th century saw the establishment of a number of ironworks in Norway, based on the need of the Danish king for iron for ships, armaments and other military purposes (Jakobsen, 1997). Based on local finds of iron ore, the Danish king issued a royal letter of privilege for an ironworks in Lesja in 1660. The history of the Lesja Iron Works is described by Berg (1983, 1984, 1985, 1986) and Jakobsen (1997). The letter of privilege states that the ironwork had a circumference from the Lesja rectory to the east and eight old Danish miles (i.e. 60 km by road; 1 old Danish mile = 7,538.48 m) to the west towards Romsdalen. Applying this type of circumference to a settled area had large repercussions.

The letter of privilege states that all forests, rivers and waterfalls within the circumference could only be used in accordance with the wishes of the ironworks owners. The timber was needed for the buildings of the ironwork, for charcoal and for firewood; the water was needed to produce power. The farmers were obliged to work in the ironwork if needed, with a payment decided by the owners. They also had to deliver charcoal at a fixed price. Elsewhere in Norway this kind of forced labour had led to considerable unrest among the peasants. This was not the case in Lesja, where farming was marginal, and the possibilities of extra income were welcomed.

The cutting down of the forest started in February 1659, and the first charcoal kilns were presumably constructed shortly after. The local lake was dammed. The first iron production started some years later. In 1718 a visiting official from the mining authorities described the forest as mostly cut down and the remaining part heavily affected. The Iron Works was never a profitable business as the amount of ore was less than anticipated, and production happened only intermittently until 1812, when the Iron Works was finally abandoned.

The remains of the Iron Works today consist mainly of the Iron Works itself with remains of one of the furnaces, the mines about 13 km further west and large numbers of charcoal kilns in the surrounding forests. In addition, the lake Lesjaskogvatnet, which is on the watershed between east and west, is still dammed at a somewhat higher level than the original lake here. The forest has re-established itself.

In 2013, the entire forested valley in Lesja was mapped with Airborne Laser Scanning (ALS). Hundreds of charcoal kilns were immediately visible in the ALS data (Figure 1). They had a varied topographical expression. Some kilns had a ditch surrounding them (Figure 2), some had pits in their circumference (Figure 3), while others had a combination of the two. In addition, some kilns had a low mound inside the ditch/pits or even pits inside the circumference.

A complete visual interpretation of the ALS data, supported by automated detection of pits and mounds (Figure 4), has led to the discovery of more than 1000 charcoal kilns in the Lesja valley (Figure 5). Of these, 183 charcoal kilns, close to the Iron Works, were field validated in 2014. The field validation showed that all charcoal kilns found during visual inspection of the ALS data were real. In addition a small number of undetected kilns were found during the ground survey. It was also noted that some of the kilns showed signs of reuse.

With more than 1000 mapped charcoal kilns, the Lesja valley provides a good data set for assessing the usefulness of deep learning in archaeological mapping. In this paper we hypothesize that charcoal kilns may be detected, to a large extent, automatically in ALS data by using deep learning approaches. A detection scheme based on a pre-trained deep Convolutional Neural Network (CNN) and a Support Vector Machine (SVM) is developed. The features extracted by the CNN are also used to estimate the size and precise localization of the charcoal kilns.

A note on terminology: in this paper, the term 'feature' is used to mean a scalar measurement or derived value, as used in the machine learning literature (e.g. see Hastie *et al.*, 2009, p. 1). These scalars are often grouped into a feature vector. On the other hand, the archaeology literature has, in general, adopted the use of 'feature' from the geographic information science, to mean an object (point, curve or polygon) which has geographic location and, optionally, attributes.

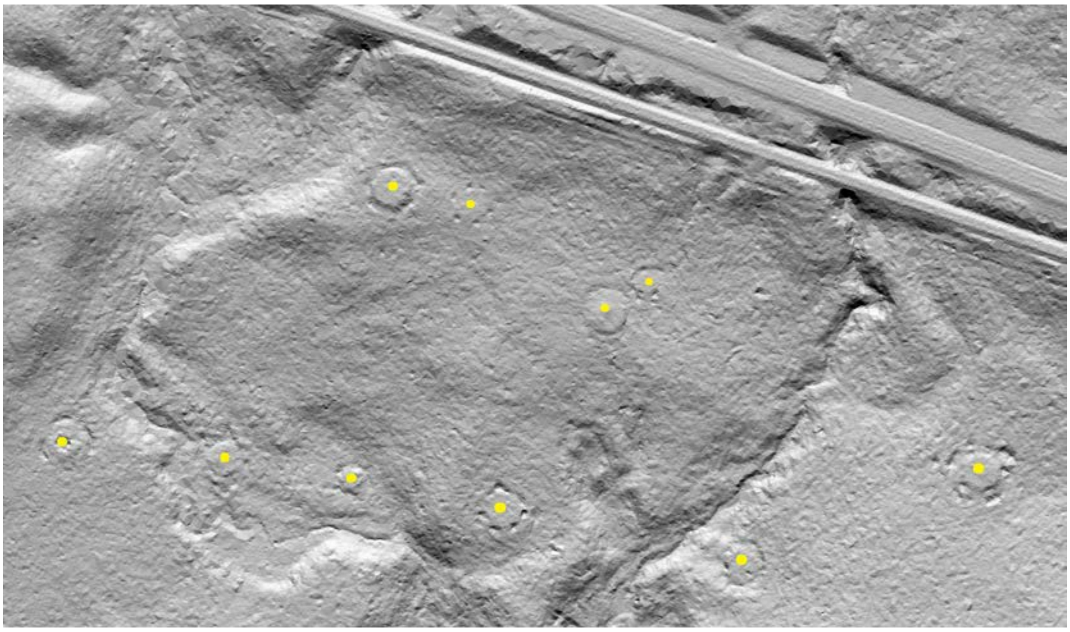

Figure 1. Hillshade visualisation of ALS data for a 356 m × 209 m area, with 10 clearly visible charcoal kilns, indicated by yellow dots in their centre positions.

Figure 2. A charcoal kiln with a flat central mound and a shallow circular ditch along the circumference.

Figure 3. A charcoal kiln with pits along the circumference.

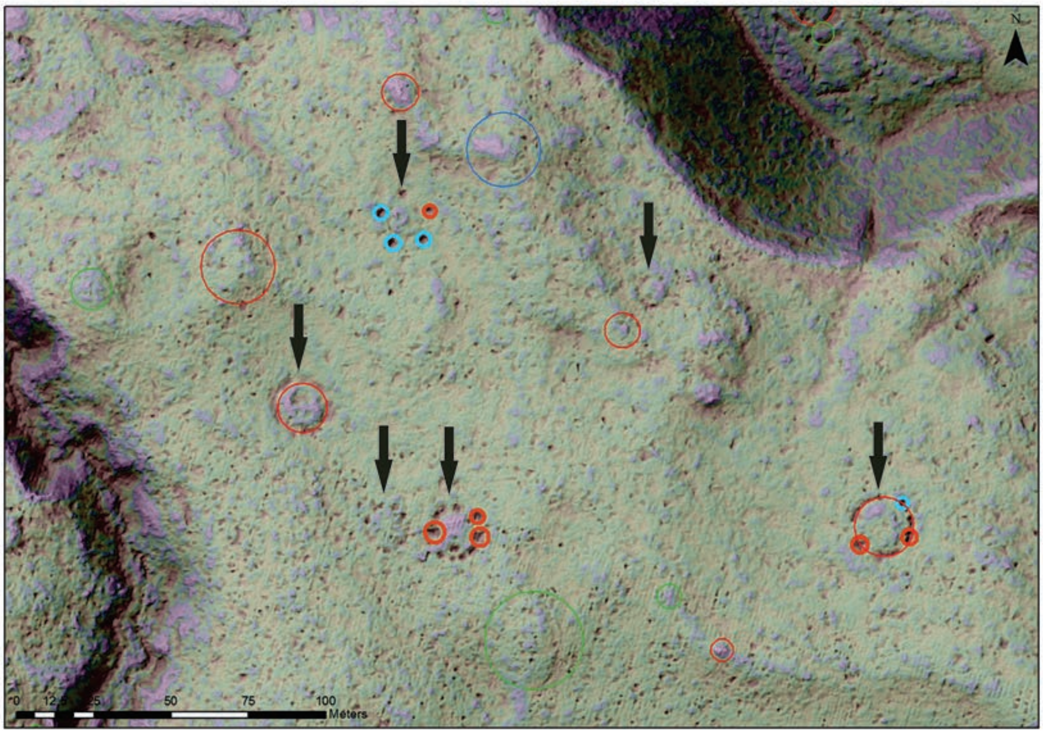

Figure 4. Example of charcoal kilns marked by automated detections of confidence levels 3 (medium, green), 4 (medium high, orange) and 5 (high, blue). Thick lines are detected pits, thin lines are detected mounds. Black arrows point to charcoal kilns.

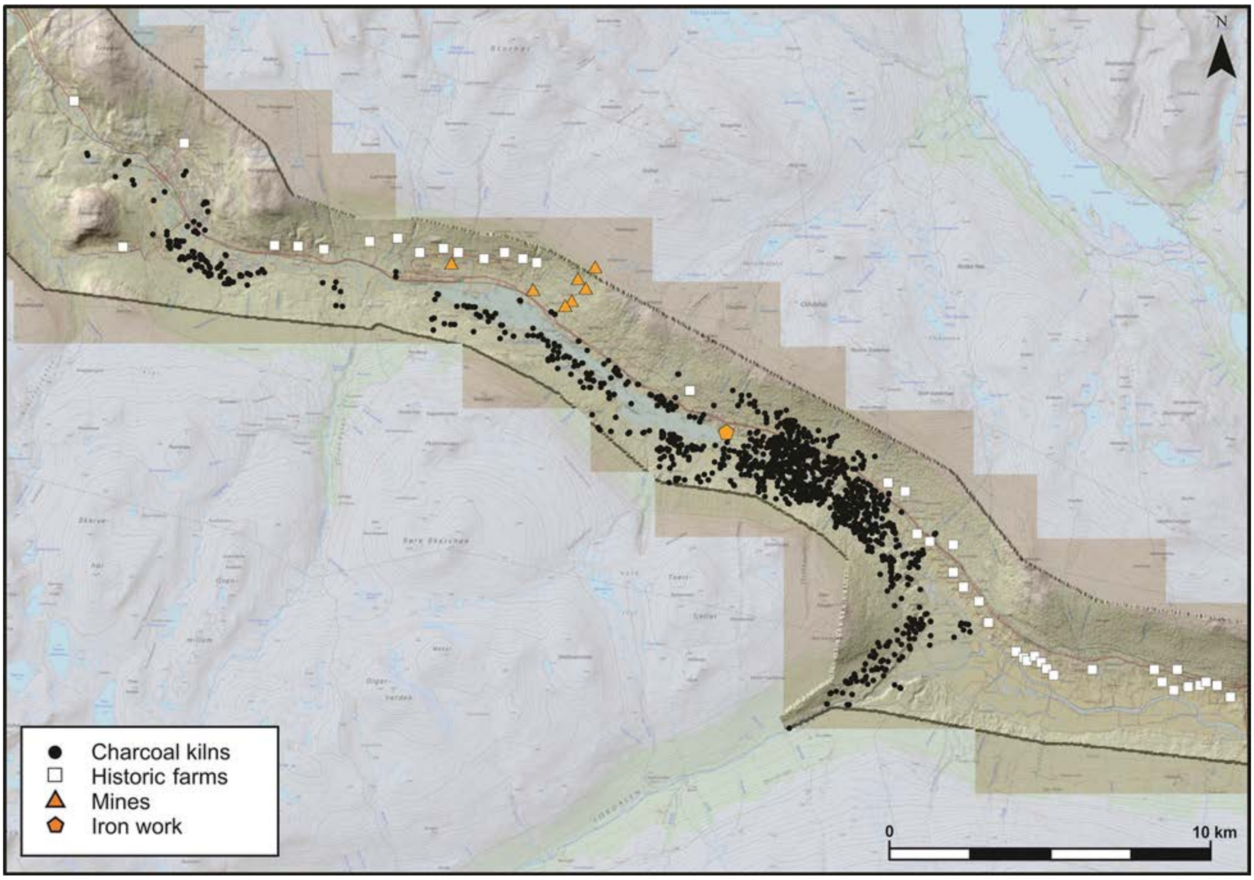

Figure 5. Detailed archaeological mapping of charcoal kilns in the Lesja valley.

Data and methods

Airborne Laser Scanning data

In 2013, ALS data was acquired by TerraTec AS for the entire forested valley of Lesja municipality, Oppland County, Norway, using a Leica ALS70 instrument. The quality of the data is five first returns per m². From the ALS points that have been classified by TerraTec AS as ground, a Digital Terrain Model (DTM) of 0.2 m resolution was made.

Training data

The training data consisted of a set of 375 validated charcoal kiln locations at Sandom in Lesja municipality, Oppland County, Norway, with a corresponding DTM derived from ALS measurements. From the same area we also have 10,027 lookalike locations from automatic heap detection, by excluding heaps that overlap confirmed charcoal kilns.

For each kiln and lookalike location, a 101 × 101 pixels (20.2 m × 20.2 m) sub-image, centred on the location, was extracted. The contrast and mean values were normalized to achieve equal contrast and equal mean value for all sub-images, and the pixel values limited to the integer range 0–255. When normalizing the contrast, the scaling factor was limited to be 25 or less. Then, rotated and flipped versions of each sub-image were made, resulting in eight versions of each sub-image (four rotations, 0, 90, 180 and 270 degrees, combined with flipped vs. non-flipped). This increases the training set, and reduces possible directional terrain biases (e.g. that many kilns may appear in south facing slopes may be a coincidence of the selection of training data and not necessarily a trend in the entire Lesja valley, or other landscapes with charcoal kilns).

Deep Convolutional Neural Networks

Detection and classification of objects in remote sensing images are often challenging tasks (e.g. see Larsen *et al.*, 2013; Trier and Pilø, 2012; Solberg *et al.*, 2007; Xu *et al.*, 2010; Zhang *et al.*, 2014), mainly since it is hard to design image features that are able to capture the visual information needed for robust detection and recognition. A common characteristic of the features applied in remote sensing recognition applications, is that they are to a great extent handcrafted and relatively simple (e.g. Larsen *et al.*, 2013; Brekke and

Solberg, 2005). The limited information captured by the handcrafted features has often resulted in a reduced performance metric compared to recognition performed by humans.

Krizhevsky *et al.* (2012) demonstrated that Convolutional Neural Networks (CNNs) obtained substantially higher image classification accuracy on the ImageNet Large Visual Recognition Challenge (ILSVRC) (Russakovsky *et al.*, 2015). Their success was a result from training a large CNN on 1.2 million labelled images, and by using more efficient strategies for training the network (e.g. rectifying linear units and "dropout" regularization"). In order to train a CNN with performance metrics comparable to the ones reported by Krizhevsky *et al.* (2012), a substantial amount of labelled training images is needed, and preferably, a Graphics Processing Unit (GPU) in order to speed-up the processing time. For many applications this is not feasible. However, a 'small data approach' is feasible. It has been successfully demonstrated that the features extracted from a deep CNN, carefully trained on the large ImageNet database, may be applied as generic feature representations and thereby applied to perform a wide variety of vision tasks (e.g. see Razavian *et al.*, 2014; Chatfield *et al.*, 2014; Azizpour *et al.*, 2015; Salberg, 2015).

The approach we will apply to detect cultural heritage from ALS data is such a 'small data approach', where we apply a deep CNN to extract image features from a DTM derived from the ALS data. The resulting feature vectors are then classified by a linear support vector machine.

Feature extraction

The feature extraction module is based on the CNN applied by Krizhevsky *et al.* (2012) to win the 2012 ImageNet contest. Since the ImageNet database consists of variable-resolution images, Krizhevsky *et al.* (2012) down-sampled the images to a fixed resolution of 256 × 256 by first rescaling the shorter side to a length of 256, and then cropped out the 227 × 227 central patch of the resulting image. As a final pre-processing step the mean activity over the training set was subtracted from each pixel. The CNN proposed by Krizhevsky *et al.* (2012) has 60 million parameters, where the last hidden layer (the layer prior to output category mapping) consisted of 4096 features. The CNN classified an image into one of 1000 categories, and was trained using 1.2 million training images and 50,000 validation images from the ImageNet database.

In order to apply the CNN proposed by Krizhevsky *et al.* (2012), we extract overlapping sub-images of 101 × 101 pixels (20.2 m × 20.2 m) with a stride of 1 meter across the whole DTM. These sub-images are then resized to 227 × 227 to fit the input dimension of the CNN, and sent through the network. Since the CNN is not trained to distinguish cultural heritages from look-alikes, we ignore the last layer (that performs the mapping to one of the 1000 categories), and consider the last hidden layer. The 4096-dimensional feature vector (Figure 6) is extracted from this layer for each object proposal by propagating the resized sub-image through the CNN.

Linear Support Vector Machine

CNN features were extracted from each of the now 3000 true kiln sub-images and 80,216 lookalike sub-images. The 4096-dimensional feature vectors extracted by the CNN are first scaled to unit norm, and then applied as input to a linear SVM classifier. The reason for choosing a linear classifier is that the dimension of the input feature vectors is high, and we therefore expect them to be linearly separable in the feature space. To perform the SVM classification we apply the Scikit Learn library in Python. The cost parameter in the SVM classifier was equal to 10 (selected by cross-validation).

Classification

The CNN was pre-trained on millions of natural images, resulting in 4096 high-level image features for each input image. The final tailoring to the problem of detecting versus rejecting that an image contains a charcoal kiln was done by training a linear support vector machine classifier with the 4096 features as input.

In the classification step, the eight combinations of rotation and flipping were fed into the CNN, and the resulting feature vectors were merged by averaging. This merged feature vector, of dimension 4096, was then classified by the linear SVM as either being a charcoal kiln or not.

Estimation of kiln diameter

In addition to detecting the charcoal kilns in the DTM, we are also interested in estimating the size of the kiln. CNN feature vectors may be used to predict local image properties in images (Razavian *et al.*, 2015). We formulate the kiln size estimation as a linear estimation problem

$$\hat{s} = \hat{w}^T f$$

where $\hat{s}$ is the estimated kiln size, f is the CNN feature vector, $\hat{w}$ is a 4096-vector estimated from the training data using ridge-regression (e.g. see Hastie *et al.*, 2009).

Validation on training data

Using the trained SVM, each feature vector was classified as kiln or lookalike. The confusion matrix

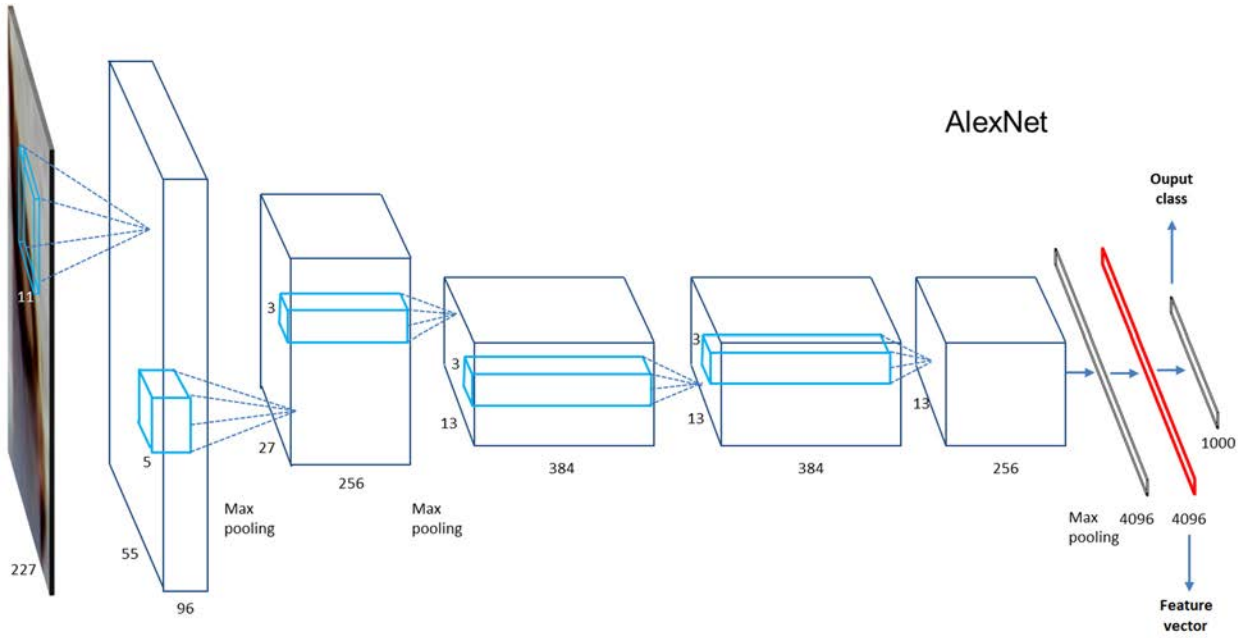

Figure 6. AlexNet, the convolutional neural network applied by Krizhevsky *et al.* (2012). The second last layer (red), of dimension 4096, is applied as feature vector for object detection and classification.

(Table 1) shows that we are able to predict the kilns with very high accuracy, even though the classification is very unbalanced (375 kilns versus 10,027 lookalikes). The average accuracy was 99.1%.

	Predicted kiln	**Predicted lookalike**	**Classification error**
True kiln	317	58	0.155
True lookalike	35	9992	0.0035

Table 1. Confusion matrix obtained from 20-fold cross validation.

The validation of the kiln size diameter estimator shows that we can predict the diameter to some extent (Figure 7). The mean-square-error (MSE) and coefficient of determination (R^2) were equal to 14.2 m^2 and 0.61, respectively.

Automatic detection

Although the training was done on specific image positions, the resulting classifier is run on entire images, using a sliding window and 1.0 m (5 pixels) steps. The classification indicated the presence or absence of kilns within each window position. This results in a contiguous area of kiln presence for each detected kiln (Figure 8).

Results

The method was applied on a 3 km × 3 km test area (Figure 9). Of the 423 charcoal kilns that had previously been identified by archaeologists, the automatic method was able to identify 363. The method also detected nine possible kilns that were previously overlooked by archaeologists. Therefore, 60 previously identified kilns were missed by the method. The number of false positives was 220 (Table 2).

	Manual: visual in DTM + field visit	**Deep learning**	**Traditional pattern recognition**
Detected kilns	423	372	304
Missed kilns (false negative)	9	60	128
Total kilns	432	432	432
False positives	0	219	780
Total predicted kilns	423	591	1084
False negative rate	2%	14%	30%
False positive rate	0%	37%	72%

Table 2. Results of automatic charcoal kiln detection.

Of the 363 kilns that were correctly identified, 13 kilns had incorrect centre position, which means that the true centre position is barely within the predicted kiln boundary.

The previous identification by archaeologists was done by visual inspection of the DTM followed by field confirmation. As an aid to this task, automatic detection of pit and heap structures had been done, using traditional pattern recognition methods (Trier and Pilø, 2012; Trier *et al*., 2015b). These methods gave higher false negative rates and false positive rates than the new method, based on deep learning (Table 2).

The detected kilns vary in their topographic expression (Figure 10). In traditional pattern recognition, one might have needed to use more than one class to represent different types of charcoal kiln. This is also possible with deep learning. However, the deep CNN was able to represent these variabilities using one class only.

The kilns that were not detected typically have a less distinct topographic expression (Figure 11) than the ones that were detected (Figure 10).

The nine possible kilns that were detected by the automatic method need field verification. However, from visual inspection of the ALS data, they are very likely to be true charcoal kilns (Figure 12). On the other hand, many of the other predicted kilns are natural terrain structures (Figure 13).

Discussion and conclusions

We have demonstrated that deep CNNs may be well suited to perform object recognition tasks in DTM images. The CNN + SVM based system was able to detect 84.5% of the known true kilns. Of the structures that the method reported to be kilns, 90% were true kilns and 10% were lookalikes. Many of the true kilns that were missed are also difficult to detect for a non-trained human reader. Please note that this performance is evaluated using the same geographical area as the training data. The difference is that the training data contained selected kilns and lookalike locations, excluding kilns close to the border, while the test was done on all image positions at 1.0 m intervals. The main reason for this was to utilise the area containing the 183 charcoal kilns with field verification. Ideally, separate areas for training and testing should be used; however, this would require more field work.

The design of the CNN is a challenging task. We have applied the same net as Krizhevsky *et al*. (2012), and applying this CNN architecture to compute the features

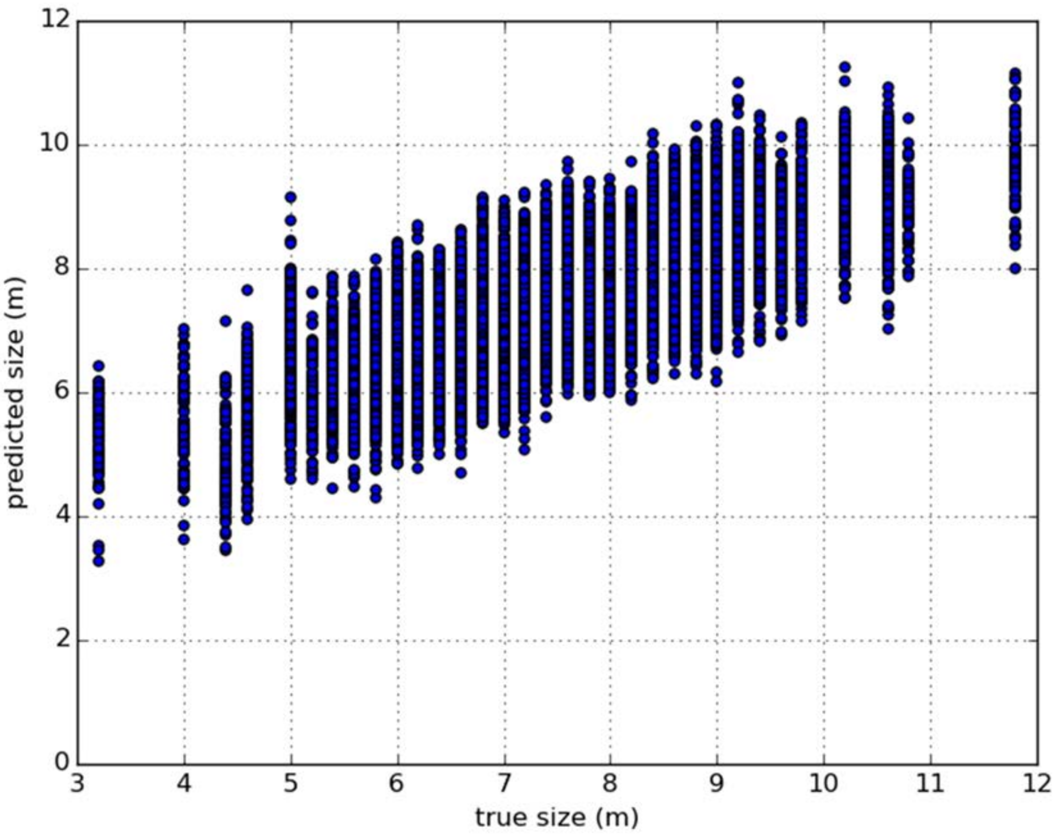

Figure 7. True kiln diameter versus predicted kiln diameter.

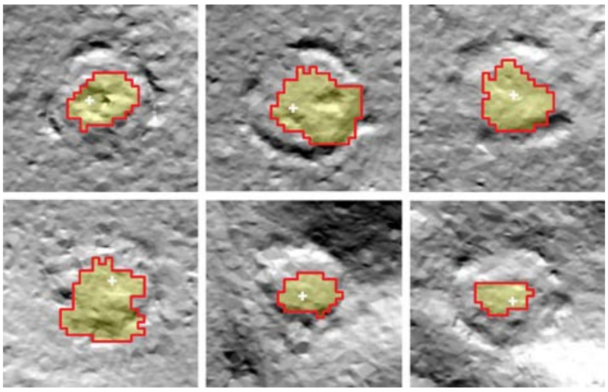

Figure 8. Examples of detected areas of kiln presence (yellow), superimposed on detailed views of hillshaded DTMs.

is most likely not ideal for our application since neither DTM images nor kilns are present in the ImageNet database. There are many aspects of the CNN that need to be evaluated, e.g. the use of multiple crops, including rotation of the object, the dimension of the cropped image and the use of other channel combinations. Finally, performing a fine-tuning of the network instead of applying a SVM at the network output should be entertained. All details are of great importance with respect to the performance. Moreover, there is no colour information in the DTM images, which is not the case in the ImageNet database, and the objects are rather special (kilns). An increase in performance is expected if using a CNN with optimal network architecture, trained on a large collection of relevant images.

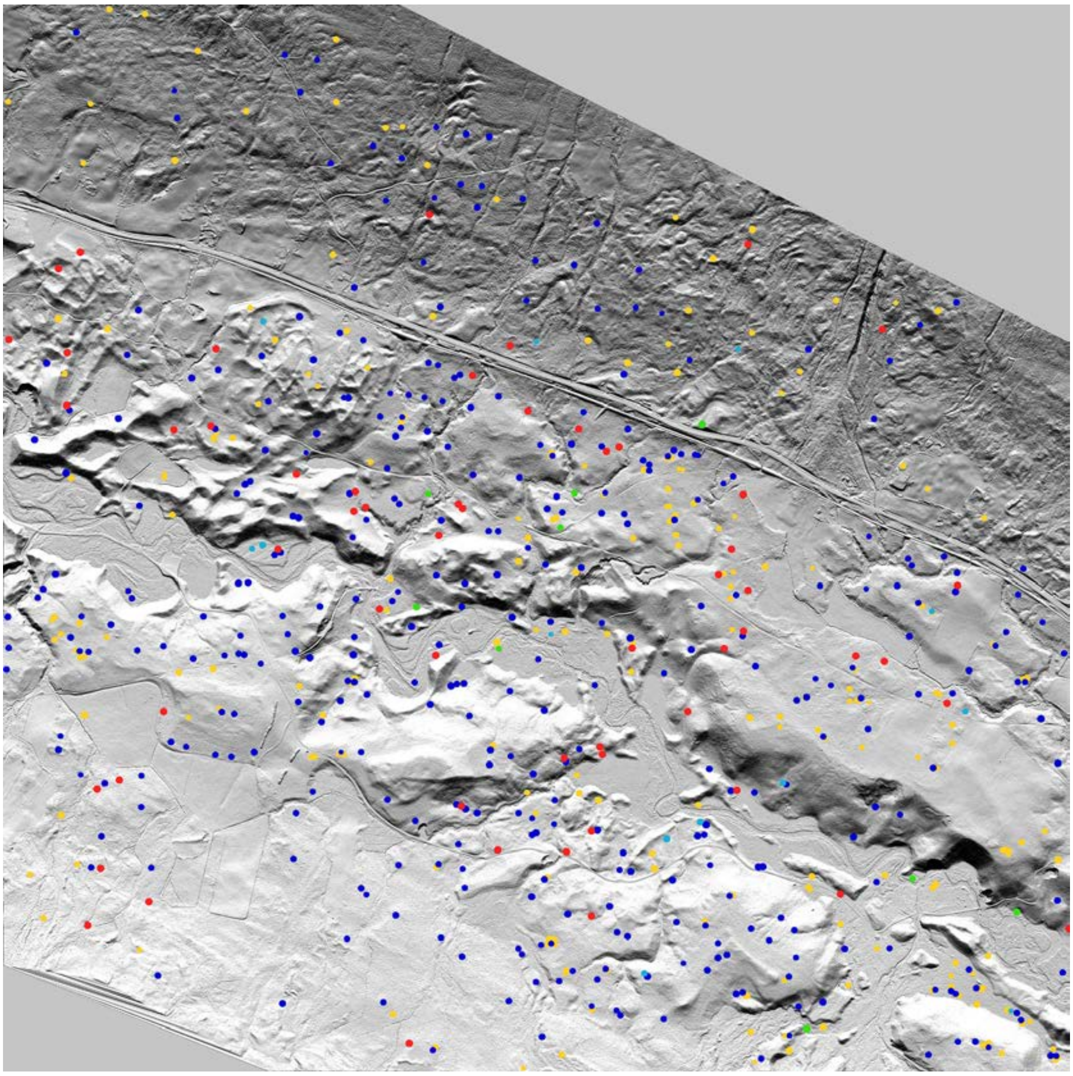

Figure 9. Result of automatic charcoal kiln detection for the 3 km × 3 km test area. Blue and cyan dots: 363 confirmed charcoal kilns detected automatically; of these, 13 (cyan) have wrong centre position. Yellow and green dots: 229 predicted as kiln by automatic method, but do not match kilns confirmed by archaeologists; however, nine of these (green) are believed to be charcoal kilns previously overlooked by archaeologists. Red dots: 56 confirmed charcoal kilns missed by automatic method.

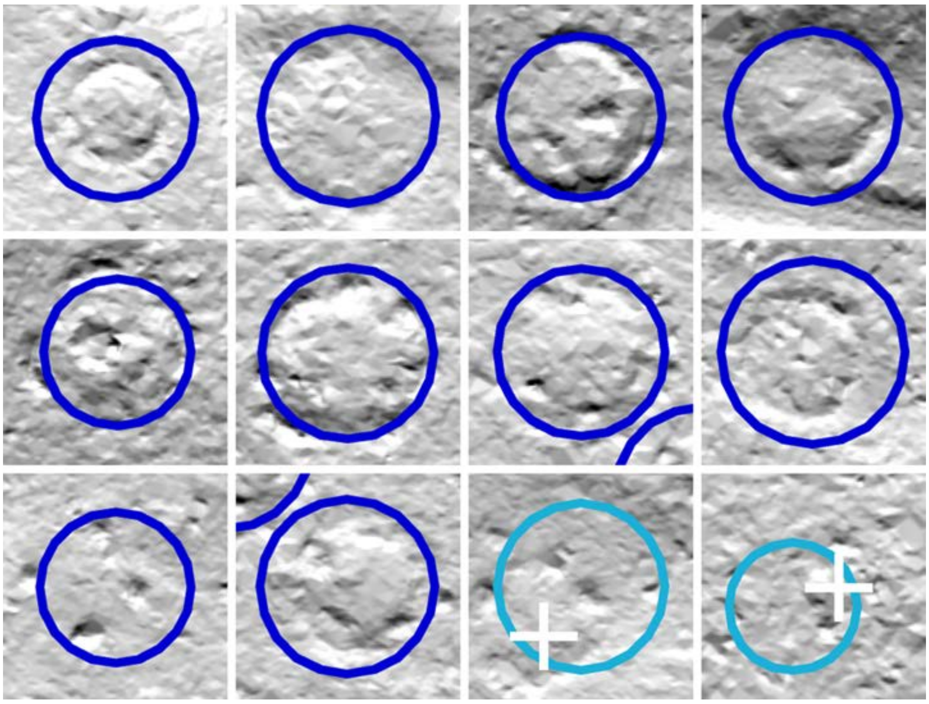

Figure 10. Examples of detected kilns. Blue or cyan circle: automatic detection. At the bottom row, the centre right and far right, the detected kilns have their centre positions one radius off the centre position that was marked by archaeologists (white cross).

A shortcoming that needs to be addressed is the lack of exact locations of the detected kilns in the CNN-based approach (Figure 8). This is due to the fact that the net recognises whether a kiln is present in a sub-image, but not the precise location within the sub-image. Improved localization accuracy may be achieved by predicting the SVM confidence values for each grid location, and apply non-maximum suppression to the confidence values. Then we may be able to distinguish two nearby kilns.

Although the results are good, we have identified a number of possible improvements:

1. To allow for efficient detection in large ALS datasets, the CNN may be implemented using a fully convolutional neural network (Long *et al.*, 2015). This avoids the sliding window approach. However, the image normalization that is applied is non-standard, and is not easy to include in a fully convolutional scheme.
2. One may explore fine-tuning of the CNN with median frequency balancing of the cross-entropy loss function (Kampffmeyer *et al.*, 2016). This may improve the error rate.
3. Another procedure which may improve the performance is to run the algorithm several times on the training site. After automatic detection, false positives are added to the

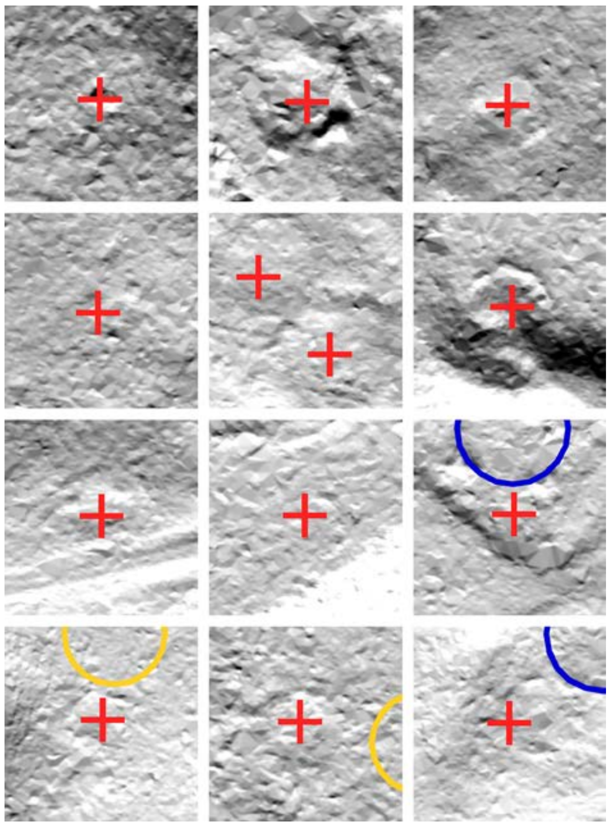

Figure 11. Examples of kilns that the automatic method missed. Red crosses are the kiln centre locations as marked by archaeologist during field verification.

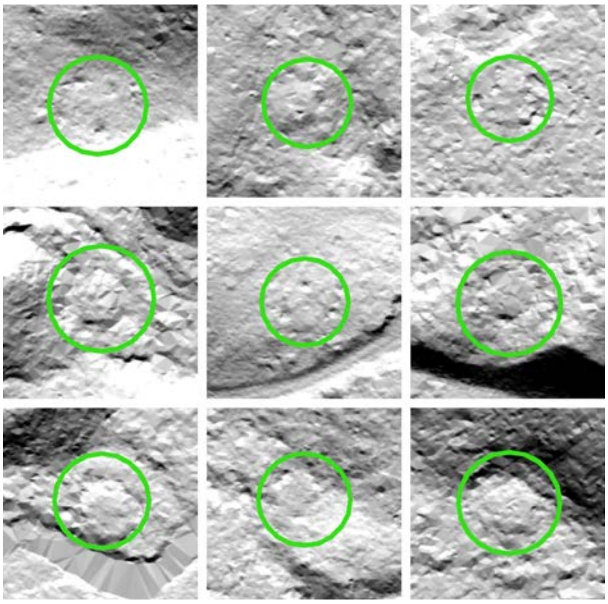

Figure 12. The automatic detection results include nine structures that are predicted as kilns by the automatic method, confirmed as possible kilns by visual inspection, but lack field verification.

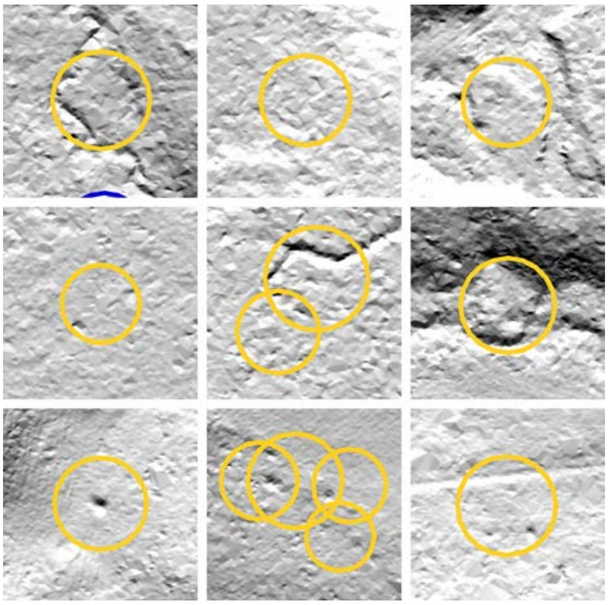

Figure 13. Examples of false kiln predictions.

training data. Then, training is repeated, followed by automatic detection. The iterations are stopped when convergence in classification performance is obtained.

4. At the moment, the automatic method detects kilns in a yes/no fashion. It may be possible to rank the detected structures based on the CNN feature vectors.

The CNN-SVM approach is generic, and may be applied to other cultural heritage structures as well. We have previously developed automatic detection methods for pitfall traps in hunting systems and charcoal burning pits in iron extraction sites (Trier and Pilø, 2012) and grave mounds (Trier *et al.*, 2015b), using traditional pattern techniques. However, the false positive rates were much higher than we presently obtain with deep learning on charcoal kilns. In a preliminary study, we applied the CNN-SVM approach to successfully detect pitfall traps in ALS data from Olstappen, with the same degree of accuracy as for the kilns in Lesja. Although our current CNN-SVM method is designed to detect one type of archaeological structure, it may be extended to discriminate between several types of archaeological structure, provided there is a sufficient amount of labelled training examples for each type of structure.

The CNN-SVM approach also has potential application in automatic detection of archaeological structures that we have yet to address in this project. In another project, forest roads are being detected by using deep learning (Trier *et al.*, 2016). Linear structures, like stone fences and hollow ways, may be detected by a similar method.

As a conclusion, the proposed method, based on deep learning, is better than our previous attempts at semi-automatic charcoal klin detection based on traditional pattern recognition methods. The new method detects more true charcoal kilns and has a manageable number of false positives.

Acknowledgements

This research was funded by the Norwegian Directorate for Cultural Heritage (Riksantikvaren). For more information on the project, please visit http://earthobs.nr.no and select 'CultSearcher'.

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Documenting Facades of Etruscan Rock-Cut Tombs: from 3D Recording to Archaeological Analysis

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Abstract:
Due to the character of tuff stone, facades of Etruscan rock-cut tombs suffer from heavy erosion caused mainly by water and vegetation. Carved decorations as well as inscriptions are slowly vanishing, and rarely preserved detached fragments of decorations are scattered around sites and museums. It is about the right time to try to find a solution against the degradation of these monuments and preserve the information about this kind of Etruscan rock art. This study examines a multi-image photogrammetry as a tool for the documentation, digital preservation and archaeological analysis of the tomb facades, which is based on increased readability of worked surface and other actions which allows a virtual environment. Furthermore, the advantages, disadvantages, possibilities and limitations of this technique applied on this specific kind of rock art are evaluated. Moreover, I explore new ways of the further use of acquired data in virtual reconstruction and virtual anastylosis.

Keywords: Etruscan, tomb, 3D documentation, virtual anastylosis, virtual reconstruction

Introduction

This paper presents a synthesis of the results that form a part of my Master thesis and up-to date results of ongoing research from my Doctoral thesis at the Institute of Classical Archaeology, Charles University in Prague, Czech Republic. Etruscan rock-cut tombs with decorated facades are a unique kind of architecture that proves that Etruscans were masters in utilising the natural environment for creating their architectural works. They are located only in the area of the inland southern part of the principal territory of the Etruscans (historical Etruria), now in the Tuscany and Lazio regions in Italy. In this zone the Etruscans began to construct their tombs by cutting them into the bedrock around the second quarter of the 6th century BC. The tradition vanished around the beginning of the 2nd century BC with the increasing Romanisation of Etruscan society and culture. The area of the rock–cut tombs has a particular landscape that is characterised by volcanic tuff stone, vast flat plateaux, deep canyon–like valleys with steep cliffs created by rivers, and crater lakes. The tombs were excavated in natural vertical cliffs of volcanic tuff stone which is very porous and contains inclusions of carbons. It is very soft, easy to cut and work into various shapes. The Etruscans used this character of the stone in the construction of various kind of architecture, not only for the tombs but also for roads, tunnels and cisterns. Some of the rock–cut tombs are supplemented on the outside part with constructions built with the excavated blocks of tuff. The tombs have burial chambers excavated inside the bed-rock and are accessible through the corridor — *dromos*. The outside part of the tombs — the facades have also an elaborated surface in various dimensions and shapes, reproducing mainly architectural elements, but in rare cases, also splendid floral and figural motifs and inscriptions. They span from small and simple to the monumental, reproducing the architecture of the temple. In the Archaic and Classical period the burial chamber had an entrance in the facade, but since the 4th century BC in the Hellenistic period, the facade and the burial chamber were constructed separately. The burial chamber is not directly behind the facade of the tomb, but situated under it. It is much simpler and not particularly decorated, only seldom decorations with imitations of the cassettes on the ceilings are found. Facades are a more important part of the tomb also for understanding the evolution of the decorative styles, and they can help to identify the chronology of the tombs, as the burial chambers are mostly robbed and don't contain sufficient material for chronology (Maggiani, 1994). Naturally, facades are also more exposed to weathering; the main causes have already been the subject of scientific research (Ciccioli *et al.*, 2009). The irreversible changes in decoration caused by erosion can also be identified by comparing the drawings of the first explorers and archaeological drawings made during the excavations conducted throughout the 20th century with the current state. From these comparisons is obvious that the details are slowly diminishing (Canina 1846–1851; Carter, 1974; di Paolo and Colonna, 1978).

Figure 1. Comparison between readability of mesh and photo of the facade of Tomba della Sirena *in situ*.

The aim of the study

The alarming state of the conservation of the monuments is not the only reason to look for a way to record and preserve as much information as possible about the surface of the facades. The aim of the study is also to examine a close-range multi-image photogrammetry technique applied on several examples of Etruscan rock-cut tomb facades. The main focus is on the consecutive step that comes after recording — archaeological analysis. How can data acquired by multi-image photogrammetry techniques help the researcher extract more information about these monuments and how they can deepen knowledge? Already existing are detailed architectonical drawings of the Etruscan rock–cut tomb facades, that are published in particular studies about the tombs, which conserve the detailed outline of the main shapes of the monument and are already the subject and result of archaeological interpretations (Bianchi Bandinelli, 1929; di Paolo and Colonna, 1978; Maggiani, 1994). The creation of a two-dimensional drawing of a three-dimensional object logically leads to a great loss of information. Not only is the technique of archaeological drawing limited, it is also always a subjective extraction from an objective reality. The researcher makes an interpretation, and they choose what is important, worth recording and highlighting, and what is not important, and therefore some information is lost. In fact, because of the degradation and slow deformation of the monument caused by erosion change, it can never be seen again in the same condition. Therefore, saving the primarily obtained data can serve for the revision and assessment of the older interpretations, or for evaluating different contemporary interpretations, confronting them with objective data or with knowledge based on the better readability of the surface thanks to the various tools of the 3D software (Figures 1 and 2).

Electronic data that preserves information about the whole three-dimensional surface of the rock-cut facade could also serve as an objective copy of the surface available for sharing with all researchers, the community and the public. Moreover, a virtual environment allows us to perform many actions with 3D models that are impossible in the external locations of the Etruscan rock-cut tombs. Direct contact isn't needed and could harm a monument which has a fragile crumbling surface. The majority of tomb facades are located in a complicated landscape. For example, the creation of accurate drawings is not an easy task. Access to some of the tombs is very difficult or even impossible. The facades, due to their size, are also inaccessible without equipment and this can be overcome by

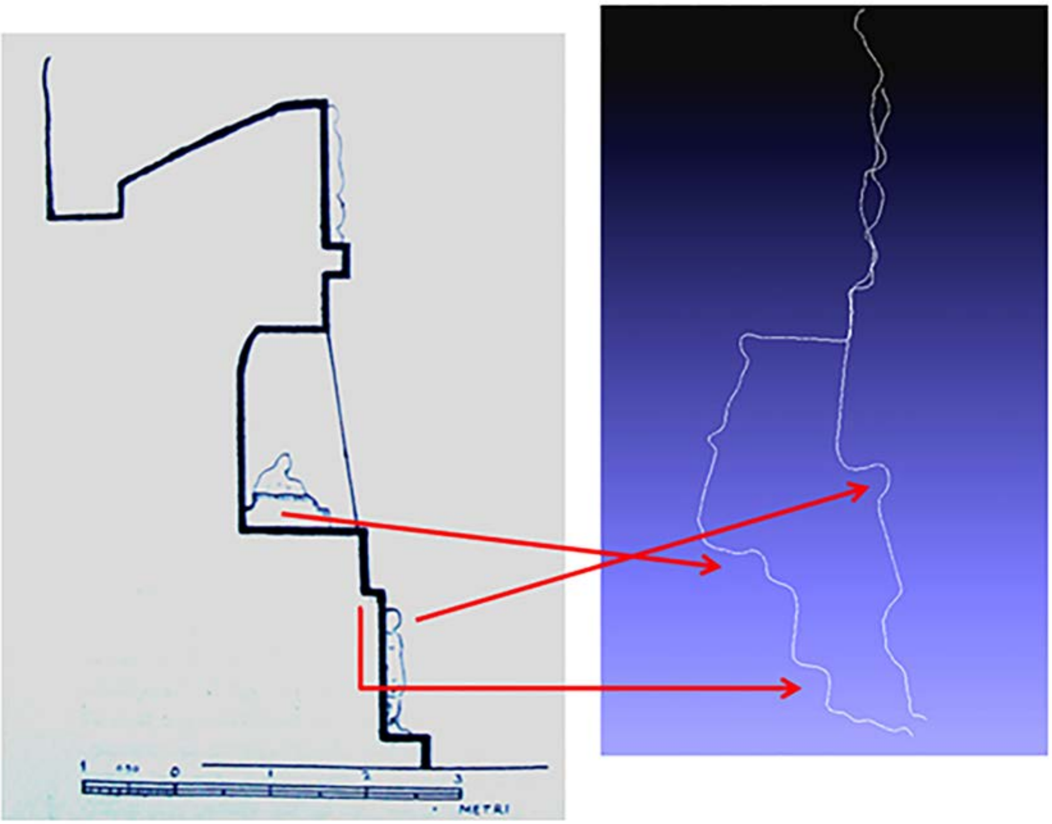

Figure 2. Tomba della Sirena — comparison between two sections of mesh and drawing of the section published by R. Bianchi Bandinelli (1929) in *Sovana*. Arrows point out to the different position of the same details of the tomb facade.

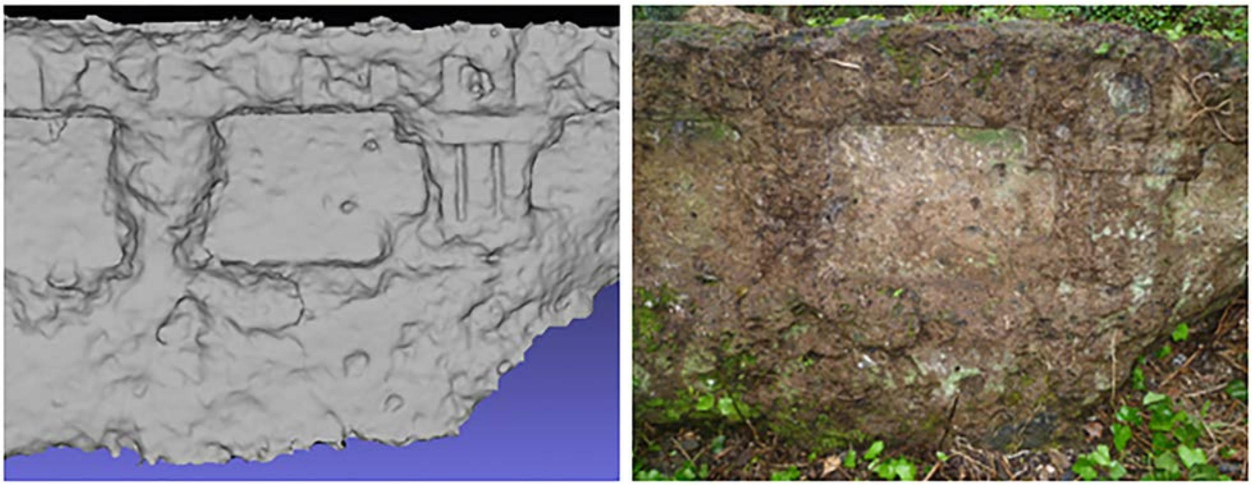

Figure 3a (left) and 3b. A comparison between same detail of a fragment from Tombe doriche; 3a) 3D model in Meshlab, 3b) photo of the same detail of the fragment *in situ.*

scanning them from an appropriate distance or with a camera mounted on a monopod or drone. In the case studies presented in this study, the surveyed facades are situated in cliffs that are between 5 and 20 meters in width and height. Important characteristics of the multi-image photogrammetry technique, which also led to its choice, were the simplicity of hardware needed for acquiring the data, user friendly software, it's suitability for surveying external objects, and its low cost when compared to other techniques, such as laser scanning. Moreover, after documentation, preservation and archaeological analysis, the acquired data is also available for further analysis and virtual reconstruction.

The documentation — acquisition of data and used methods

For the acquisition of images, digital DSLR camera was used: a Nikon D3300, 24 Mpix with the lens AF-S Nikkor 18–55 mm, f3, 5–5,6 VR. The workflow followed the well-known method of multi-image photogrammetry techniques (Remondino and El-Hakim, 2006; Remondino, 2011; Gonizzi Barsanti *et al.*, 2012; Forte *et al.*, 2012; Remondino and Campana, 2014; Benavides López *et al.*, 2016). In the first step, the images were taken from nadiral and convergent positions, paying attention to cover each part of the object with at least two images. Secondly, on each tomb, measurements between some recognisable points were taken manually with a reference scale. During the acquisition of images, settings were adjusted in manual mode: low ISO, good depth of field, and images were taken in RAW format. Afterwards, RAW images were processed to adjust colour and exposure and to create uncompressed JPEG images. Images were processed with Agisoft Photoscan and the results were high resolution dense point cloud and textured 3D model.

The archaeological analysis

Multi image photogrammetry allows us to create a very high-resolution survey of the rock-cut facade. The virtual environment gives us the possibility of performing experiments and actions that are otherwise impossible in the external conditions of the monuments *in situ*. In this environment, we gain a whole new perspective on the studied monument and the possibilities of manipulating the 3D model. Different artificial lighting changes, various shaders and the possibility to see the pure surface of the monuments without it being distorted by the colourful surface of the stone or other natural causes, all leads to more accurate documentation (Figure 3a, 3b). Furthermore, some of the most exceptional tomb facades have preserved pieces of decoration that are detached from the original surface. These fragments are preserved at the necropolises and in museums. By creating 3D models of all the parts of the facades (that *in situ* and detached fragments), it is possible to reassemble the detached fragments with the facade in a virtual environment.

Such reassembling in reality is mostly an impossible task. For example, one part of the pediment from *Tomba Ildebranda* from the Necropolis Poggio Felceto in Sovana is reassembled and integrated in a new structure that has been created according to the supposed original appearance, and is on display in the vestibule of the museum Palazzo Pretorio in Sovana. In this case, the fragments have small dimensions and the creation of such a reality model on a 1 to 1 scale has been possible. But in the case of larger fragments, the real reconstruction can be difficult, expensive and a risky project and integrated original fragments can no longer be the subject of further studies. Then there is the question of conservation — is it better to preserve the fragments close to the original structure where they are exposed to weather changes and vandalism, or in a museum many kilometres away from the site and shown out of context, where they become only one of many anonymous objects in exposition, such as in case of *Tombe doriche*? In a virtual environment, by scanning all the fragments and the facade itself, it is possible to put together all the preserved pieces and work with them without limitations, experimenting to find their original places and create a virtual anastylosis.

Virtual anastylosis has been experimented in the case study of the so-called Doric tombs (*Tombe doriche*) from the Necropolis of Fosso del Acqualta in Norchia, and in the case study of fragments of the pediment of the *Tomba dei demoni alati* from the Necropolis of Poggio Felceto in Sovana (Barbieri, 2010). Both facades have preserved several fragments of decoration at the site in proximity to the facades, and in museums. The Doric tombs are two tombs with facades excavated in the tuff cliff immediately next to each other, and are the only ones of their kind; the closest analogies can be found in the so-called temple tombs in Sovana necropolis. The Doric tombs were constructed in two phases. The first phase took place at the end of the 4th century BC to the first half of the 3rd century BC. Burial chambers and the facades above them were cut into the bedrock. The facades have two pediments imitating temples. Under each pediment, four columns were probably excavated in full relief. At the base of the facades, two niches with benches were cut, the so-called *sottofacciata* rooms. The second phase is dated to the 2nd century BC. In this phase, the columns were removed and relief frieze with figural decoration has been carved on the wall under the pediments.

In this case study, three 3D models were created: one of the facades, one of the fragment of pediment collapsed in front of the facades, and one of the fragments preserved in the Archaeological museum in Florence. All three were put to scale according to two measured points on each of them. To understand which the original main outline of the pediments were, I created a sketch vector drawing on the base of the orthogonal image taken from the 3D model of the facade. The next step was importing all three 3D models into one project in Meshlab software. By moving the axes and changing the angles of the 3D models of the fragments, I moved them to the assumed correct position close to the 3D model of the facade. Throughout the whole process, I controlled the position of the fragments by re-creating an orthogonal image of the 3D model of the facade together with the 3D models of the fragments and visualizing it under the sketch drawing. I controlled the position by visualizing all the 3D models from various angles in Meshlab as well. This process was repeated until the position of the 3D models of the fragments was matched with the sketch drawing from the orthogonal view, and I also kept the outline of the fragments in the same line from top, bottom and side views of the group of 3D models. For the purpose of recreating the original aspect of the facade, it is not required to scan fragments in detail from all angles, but to focus on the side which is part of the visible surface of the facade. By visualizing all 3D models under different lighting conditions and using various shaders, such as Radiance scaling in Meshlab, and as well visualizing the point cloud in 'Normals' Adobe AutoCAD, the details of the carved decoration stand out (Figure 4).

In this way, I greatly increased the readability of the surface decoration that would otherwise be invisible to the naked eye. A better understanding of the surface relief leads to the creation of more accurate archaeological drawings that can also incorporate missing fragments. By combining different 3D visualizations and manipulation with 3D models, more information can be obtained in an easier manner, in respect to a manual survey on the site. Moreover, once the data is in electronic form, it is much simpler to look for stylistic analogies in other artistic objects. One example of the exceptional increase in the readability of the decoration can be seen on the low relief of the frieze carved on the wall under the pediments of the Doric tombs (Figure 4). Thanks to the details that stand out on the model, I could compare them with the relief decoration of the analogical decoration in *Tomba Giglioli* to better understand relief decoration under pediments of the Doric tombs. After the 3D models of the fragments were placed in their supposed virtual original place and, after the study of the relief decoration and analogies were done, the finished group of 3D models consisting of all three parts was imported into AutoCAD, and the drawing has been done directly on the point cloud.

Virtual reconstruction

Another further use of acquired 3D models is the creation of the 3D virtual reconstruction, and I examine this in the case study of the *Tomba della Sirena*, from the Necropolis of Sopraripa in Sovana (Carter, 1974). The aim was to preserve as much as possible of the original shape and the details of the surface and its features. The most common way of making the virtual reconstruction is to create the model from zero, following the measurements of the reference object. The 3D models built this way have mathematically perfect straight lines, planes and angles and the realistic appearance

Figure 4. Tombe doriche — mesh of the facade and fragment imported together in one project and shown with shader Radiance scaling. Increased readability of the relief decoration helps also during the process of positioning and joining the models for virtual anastylosis.

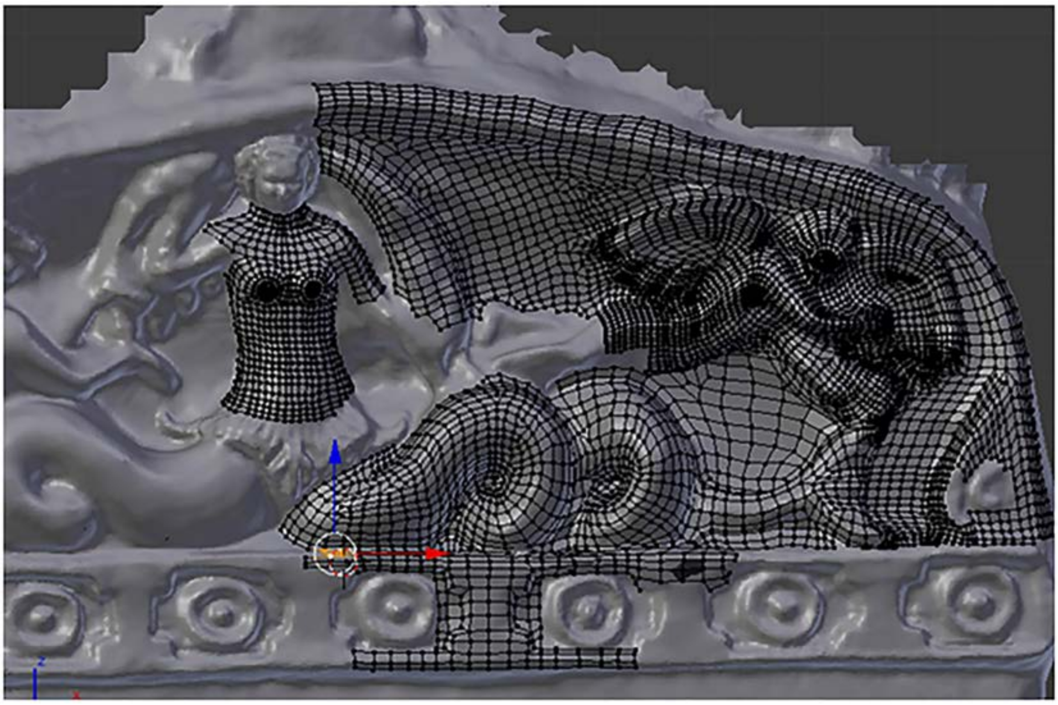

Figure 5. Tomba della Sirena — creation of the new model with retopology technique.

is achieved by texturing, shading and using various supplements such as bump maps. The less complicated the surface is, the easier it is to build it and manage by computer. I wanted to find a compromise between saving the original imperfect surface of the model of the monument and the size of the model that could still be manageable by computer. Instead of creating a completely new model based on the reference image and measurements, I continued to work with the basic model made with Agisoft Photoscan software, and therefore I modified it by sculpting in Blender software. The original appearance of the facade is not possible to identify because some parts of the facade are lost, and the rest is damaged by erosion, so the reconstruction can only be hypothetical and based on analogies with other Etruscan artefacts. As a result, it is an individual subjective interpretation. To make my own interpretation, I studied all known closest typological analogies in Etruscan art that are other tombs and cinerary urns. The parts that are the most difficult to reconstruct are lost parts inside the niche, the figure on the right side from niche, decorations on the sides and on the top of the pediment.

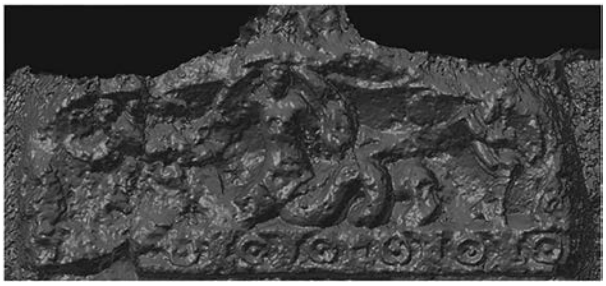

Figure 6. Tomba della Sirena — detail of the pediment, mesh resulting from acquired images.

Figure 7. Tomba della Sirena — detail of the pediment after retopology, author's hypothetical virtual reconstruction.

As the first step, the 3D model of the facade of the *Tomba della Sirena* was created in a standard process. Images were acquired with a digital DSLR camera and measurements of some recognisable points were taken. Images were processed in Agisoft Photoscan in standard workflow (alignment of images, building dense point cloud) and Meshlab software has been used

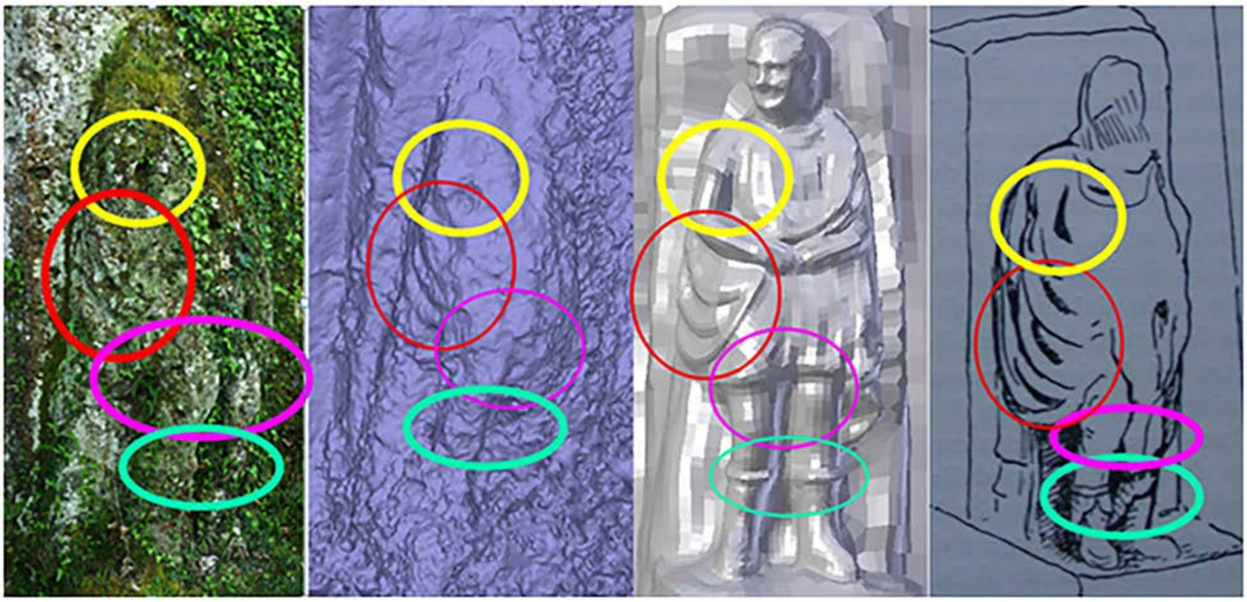

Figure 8. Tomba della Sirena — comparation of the same details: photo of the facade, mesh, author's virtual reconstruction, drawing published by R. Bianchi Bandineli (1929) in *Sovana*.

Figure 9. Virtual reconstruction — textured 3D model.

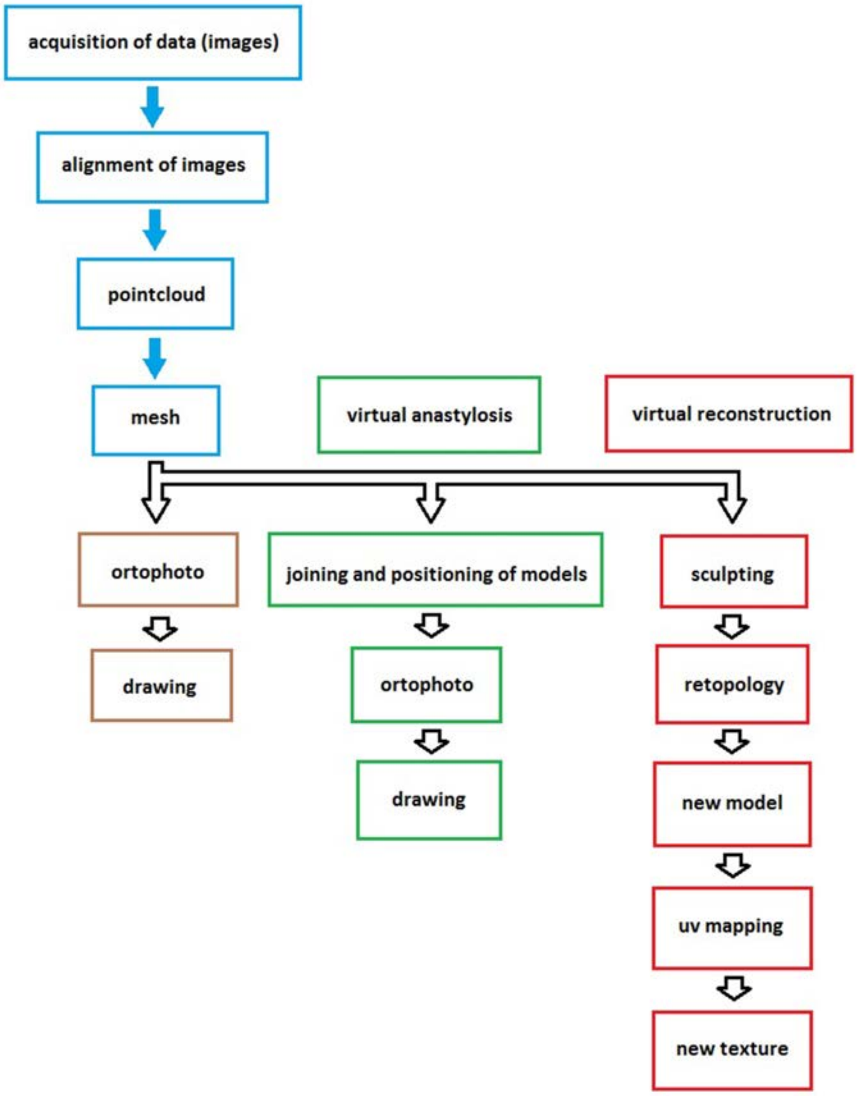

Figure 10. Diagram of the basic steps taken throughout the project.

for the mesh creation and for scaling the model. After the 3D model was finished, I had to decide how the hypothetical reconstruction would look. This required the very careful study of analogies that could give a clue how to proceed with the reconstruction of the shapes. I also studied the 3D model itself using different tools — various shaders and changing light conditions of the 3D model in Meshlab software. As a result of the increased readability, I had a better understanding of the surface of the model and it was clear how to continue in the next step. Thanks to the shader X-ray in Meshlab, it was possible to see more clearly how the execution of the tomb was actually extremely irregular. For example, it is visible on details of the niche from the top and side view, and on the walls of the facade that are not plane and corners are far from 90 degrees. In this way we can better understand how deep inside the rock the relief was cut.

The second step was actually modifying the mesh by sculpting it in Blender software. I used various brushes to smooth and modulate the surface, filling in the holes and cracks caused by erosion and the natural porosity of the tuff stone. As the basic model has a very irregular surface I had to close all holes in the mesh and make polygons more regular by repeating the re-meshing process.

After the sculpting process of the basic model was finished, the geometry of the 3D mesh was very irregular and complicated. It was not possible to create a texture on this surface. Because of this, I was looking for a solution for simplifying the geometry and decrease the number of faces of the model that would allow me to create a texture. I chose to use a retopology technique. Retopology is basically the creation of a new model on the surface of the basic model, in this case by manual positioning of new polygons. How detailed the new model is depends on the user. This new model preserves the shapes of original but is more regular and has a simpler geometry (Frank *et al.*, 2016). The higher the number of faces the more detailed and smooth the surface will be. My aim was to preserve the original shapes as much as possible. In this case, it was not possible to make retopology in some automatic or semiautomatic way because important details could be lost. The new model has to be created by positioning every single new polygon manually following the most characteristic lines and carefully choosing the position of new polygons so that important details of surface aren't lost. This phase was the most time consuming, but the result was very satisfying because both main aims were achieved. The size of the model decreased: the original sculpted model was 53 MB and the new model created by retopology was only 7.51 MB and it was much easier to manage by computer (Figures 5, 6 and 7).

The model created by retopology was suitable for building texture by un-wrapping its surface. The surface was divided in several parts to minimalize deformation of uv-map. Deformation was caused by the unequal density of distribution of polygons. Uv-maps were exported in Photoshop software as images and painted to create new texture. The choice of colours has been done on the analogies dated to same period as the tomb, that is with the *Tomba dei demoni alati*, frescoes from the tomb chambers in Tarquinia, funerary sculptures from the necropolis at Tarquinia and preserved polychromy on the Hellenistic cinerary urns (Barbieri, 2015) (Figures 8 and 9).

Conclusions

The advantages of the close–range multi-image photogrammetry technique used on the facades of the Etruscan rock cut tombs are numerous. This technique is suitable for documenting the fragile surface because it isn't necessary to touch the facade of the monument; direct contact with the monument could cause more damage and in this way we can prevent it. We are able to scan hard to access parts of the monuments. It is a faster way of collecting data compared to traditional documenting methods, such as drawings based on manual measuring. It is a low cost method compared to, for example, laser scanning. For its simplicity and low cost, it can also serve for documenting a large number of the tombs, and it is also suitable for the external environment and the rock surface. Moreover, the 3D model serves as an objective copy of the monument and for its digital preservation. The 3D models can function as a tool for archaeological analysis in a virtual environment by using different lighting conditions, shading, cutting and measuring that increases the readability and understanding of the shapes of the surface and the relief decoration. On the basis of the orthogonal image of the 3D model, on the point cloud or by cutting the point cloud of the 3D model, we can create a drawing of any desired part of the monument. Once the data is acquired and a 3D model is produced from images taken with a digital camera, it can be used in all the above mentioned ways, plus it can act as a starting point for the creation of virtual anastylosis and virtual reconstruction (Figure 10).

The main disadvantage and limitation of the close-range multi-image photogrammetry is the need for a good view of the surveyed object. The basic condition is the possibility to take images from all positions that are needed to produce a complete model without holes in the mesh. If the facade is situated in a highly inaccessible place or, as is often the case, access to it and the view of the facades is blocked by growing flora, it is not possible to acquire sufficient images from the ground. If the view of the monument is blocked by vegetation, a 3D model cannot be produced without holes and a distorted surface. This can be overcome by using a high tripod or telescopic handle for the camera or taking images from a drone. Use of this equipment as well as cleaning of the monument and its environment is standard procedure in every standard survey and thus the use of close-range multi-image photogrammetry should not be affected by these problems.

Case studies presented in this paper will be included in a catalogue that forms a part of the ongoing project of my PhD thesis. The aim is to create 3D models of selected facades of each type of facade constructed in the Hellenistic period. This catalogue will serve as a supplement for traditional historical study and also contains models and archaeological drawings based on the 3D data sets. In this supplement, it will be possible to search the database according to chosen criteria such as chronology, typology, and particular elements of decoration. As has been emphasised, the facades are important from point of view of studying the architectonical evolution of the rock–cut tomb architecture. Furthermore, erosion is an ongoing process that cannot be stopped; therefore, it would be good to preserve the state of conservation of the facades as they are in the present in order to conserve it, at least in a virtual environment, for the future. By the repetition of surveying of the monuments, it would also be possible to monitor the rate of erosion.

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Archaeological Information Systems

Mieko Matsumoto and Espen Uleberg (eds) 2018. *CAA2016: Oceans of Data*
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
Oxford: Archaeopress

Fasti Online: Excavation, Conservation and Surveys. Twelve Years of Open Access Archaeological Data Online

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Abstract
Fasti Online (http://www.fastionline.org/) is a leading provider of open access data for archaeological investigations, published online by the International Association for Classical Archaeology (AIAC). During 12 years of existence, Fasti has witnessed the transition of archaeological archives from analogue to digital and online media. Now Fasti faces major frontiers in the discipline; the pursuit of Linked Open Data (LOD), as well as the migration and reuse of legacy data as part of our new Fasti Survey service. Between 2012 and 2016, Fasti Online has participated in the ARIADNE linked data project. Concurrent with our 'open' mandate, this paper presents a reflective view on our recent efforts both as an ARIADNE partner, and as a stand-alone platform.
AIAC is grateful to its partners, L–P: Archaeology, ICCROM, KNIR, and CSAI, and to ARIADNE for providing the practical and intellectual support that has allowed our project to grow.

Keywords: Linked Open Data, CIDOC-CRM, Fasti Online, ARK, ARIADNE

Introduction

Fasti Online[1] is a valuable, forward-thinking resource as a provider of open access data; publishing reports and metadata for archaeological investigations across 14 countries. Since 2015, Fasti Online has also provided information on conservation projects as well as excavations, and now users are also able to come to Fasti for data about archaeological landscape surveys (field-walking, LiDAR and geophysical to mention a few examples). When Fasti first came online in 2003 it continued the work of the 'Fasti Archaeologici' (*Fasti,* comes from the Latin word for 'calendars' or 'register' and means a record of events), a print publication in Rome which compiled annual summaries of fieldwork conducted in the Mediterranean. The review was produced by AIAC and covered the period between 1947 and 1989. In 1998 the journal was discontinued in print. There was still a need to distribute these records, and migrating past projects into new technologies is nothing new for archaeologists (Costopoulos, 2016, Richards and Winters, 2015). In 2003 AIAC received funding from the Packard Humanities Institute (PHI) to reimagine the Fasti, and it was recreated as an online database for projects from the year 2000 onwards.

Since this time Fasti Online has acquired partners in 14 countries, and holds data and metadata in 14 languages. At the time of writing it contains 6000+ records for 3000+ sites across Europe. In addition, Fasti publishes articles through its open access, peer-reviewed journal *Fasti On Line Documents and Research* or *FOLD&R* series, which has now published 370 longer articles on archaeological sites. All of this information is released under a Creative Commons Attribution — ShareAlike 4.0 license. The data is made up of contributions from archaeologists that are entered by country administrators. By having these trusted points of contact to mediate data supplied by the wider community, obviously spurious data is filtered out before being entered. Fasti is maintained by this community of administrators, who rely on voluntary contributions from the excavators (only in Italy is this participation required by the Ministry of Culture). Each country's site is bilingual in its own language and English, and can be searched either through the map or through keywords, with filters available for more complex queries.

The website has been in continuous development by L–P: Archaeology since 2004, and is powered by the *Archaeological Recording Kit* (ARK) software (L–P: Archaeology, 2016, Eve and Hunt, 2008). Fasti Online is currently on version 3.4 with a new version expected soon. When it was launched, it was one of only a few databases providing archaeological data online, and happily now finds itself in a situation where not only is it one of many, but also that its data can be considered,

[1] http://www.fastionline.org/

enriched, and exchanged and compared with other databases, such as Archaeology in Greece Online.[2] The collaboration resulting from the ARIADNE linked data project has thus increased both its depth and its scope.

Digital repositories like Fasti Online are challenged to present reflexive and open archaeology (Morgan and Eve, 2012). Fasti has embraced this challenge by incorporating the latest technologies available throughout its lifespan. This paper comes at a time when Fasti is expanding again to bring in new types of data sets and considerations. In this paper we seek to present some of our recent initiatives, and our progress towards being a Linked Open Data (LOD) site. First we will consider our process as a partner of the ARIADNE linked data project, and second, our new project Fasti Surveys. Before doing this, this paper will have a quick introduction to Fasti Online, to provide context to later content.

The Fasti data model

The original Fasti Model sought to provide a record of archaeological activities, initially only excavations, but in 2015 the model was expanded to include conservation projects, which is managed by the *International Centre for the Study of the Preservation and Restoration of Cultural Property* (ICCROM). Therefore, Fasti primarily consisted of two levels of information — 'sites', and 'seasons'. As the database grew, we now have the capacity to present data relating to 'objects' (read 'artefacts'), which encompass the additional metadata required for conservation fieldwork.

The data stored in Fasti is essentially metadata of various archaeological endeavours, giving the user a useful means of discovery for archaeological work that has investigated a site, region, or which appertains to a certain time or archaeological period. The record for each site specifies the types of monuments, the dates of occupation, and the excavation team and sponsors as well as short 500 word summaries of the fieldwork seasons. These summaries are held in two languages, English and that of the partner country. The web-accessible front end allows users to explore the data with a 'slippy' map interface, search by monument type and date range, or create complex queries on the data using the ARK interface.

Fasti Online and first steps towards Linked Open Data

Fasti Online mints new URIs for all of its records. These URIs have Fasti Online as the root, followed by the relevant triad; the type of record that it is within the Fasti Model (a site or season), and then the AIAC number for that site. As an example see: http://www.fastionline.org/excavation/site/AIAC_282. The arguments for Linked Open Data are well-rehearsed (Haslhofer and Isaac, 2011; Kansa and Kansa, 2013), and Fasti Online has been on a trajectory towards using more Linked Open Data for some time. In 2012 the system introduced links to the *Pleiades* ancient place name gazetteer (Bagnall and Talbert, 2016) and to the *GeoNames* (Wick, 2017) modern place names list, which provides Fasti Online records with enrichment for both the modern and ancient toponyms for Fasti 'sites'. The GeoNames database is queried automatically, on-the-fly using the coordinates of the site, which are already stored in Fasti Online. The Pleiades ancient place names, however, cannot be easily resolved from the spatial coordinates, due to potential inaccuracies in the data and due to the temporal component in ancient places. Therefore, the provision of an ancient place has to be linked manually by an administrator. If an administrator believes a site in Fasti Online can be equated to an ancient place in the Pleiades gazetteer, a link can be created from the site to one or more Pleiades URIs. This gazetteer alignment is a crucial step in creating LOD, allowing the user to access relevant data stored by other providers (Simon *et al*., 2015). These links help to enrich the data held in Fasti Online by giving points of access to other sources. In turn, this link enriches the external data sources as well. It is important to note that the use of external sources does not replace or substitute data that would be stored in Fasti Online, but makes it possible to answer questions across data sets (Isaksen *et al*., 2010).

There are limitations to using external data like this. In some instances the GeoNames polygons do not have sufficient precision to correctly describe the edges of an administrative boundary, and sites will be described by GeoNames as being in the wrong area. The direct links drawn to Pleiades URIs do not suffer from this drawback. Both links however are outside of Fasti Online's control, and if and when these become unavailable, or 'closed' for any reason, the Fasti Online records will not be able to benefit from them. A similar event occurred when MapQuest, the map server, discontinued open access to their map tiles and an alternative had to be sought. This served as a salutary lesson in over reliance on out-sourcing serving data, as opposed to enrichment. The relationship with GeoNames and Pleiades serves as a healthy balance, as Fasti Online does not aim to encompass all of the potential data linked to the sites; its goal is to use these gazetteer alignments to contribute to a LOD ecosystem (Kansa and Kansa, 2013). There are many reasons to be confident about the longevity of this ecosystem, as there are many interested parties who all mutually benefit from the growth of this network of heritage data.

[2] http://www.chronique.efa.gr/

Linked Open Data — Fasti and the ARIADNE project

De facto Open Data is not simply data released under a creative commons license; it must also be easily accessible for discovery and re-use by the researcher. Fasti Online is a participant in the ARIADNE project, which has provided a great opportunity to achieve its LOD goals through an international project. The ARIADNE project has created a new extension of the CIDOC-CRM Model called CIDOC-CRMArcheo (Doerr *et al*., 2016, p. 445). Our data model was mapped to the CIDOC-CRM, the most important concepts are shown in Figure 1. Each node in the figure shows the term, how that data is sorted in Fasti Online and the CIDOC-CRM concept that maps to it (Doerr *et al*., 2016). It is important to note that this information will be presented in the forthcoming ARIADNE deliverables and reports, this paper however provides us with a great opportunity to reflect and 'show our workings' on the progress made.

A core unit of recording in Fasti Online is the season. A season in Fasti is a period of archaeological investigation that we have mapped to the CIDOC-CRM as conceptually equivalent to an 'activity' (E7 Activity), following the mappings by other ARIADNE partners (Felicetti *et al*., 2014). From this core concept the model defines the information that Fasti Online holds (the objects) and the relation (the predicate) it has to the season (the subject).

In the Fasti data model these are:

- a year in which the investigations took place (E52 Time-Span);
- a summary (E73 Information_Object);
- a report (E31 Document);
- actors (E26 Actors), and the roles that they participated in (P14.1 in the role of);
- images that represent the season (E38 Image);
- and the site (E27 Site) that the season took place at.

The site also has a number of important fragments of data attached to it. Each site has:

- a bibliography of documents (E31 Document) which references the site;
- images which represent the site (E38 Image);
- a monument type (E55 Type);
- and a location represented in the database as Latitude and Longitude (E47 Spatial Coordinates).

In our linked data representation of Fasti we only expose the coordinates which we hold: users of the LOD can resolve the details from GeoNames from the coordinates in the same way that the Fasti Online web portal does.

Periods

Fasti Online period data is stored in the Fasti Online spatial server. The CRM requires an 'E2 Temporal Entity' for the time span data. The relationship between the time span and specific archaeological periods is determined by a relational table, sorted on the Fasti each with a spatial extent and a time span. By comparing the time span and coordinates with this table the period of a site can be resolved. Currently Fasti stores its period data in its own relational database tables, but that information has been incorporated into the PeriodO data set (Buchanan *et al*., n.d.). The PeriodO project, which provides the Digital Humanities with a gazetteer for expressing and cross-referencing periods reflexively, is an exciting new development, born out of the need for a means of defining and linking period data, and Fasti Online are encouraged that PeriodO incorporates 212 of our period definitions.

Future developments might update Fasti to use this external store of periods alongside the internal one, enabling Fasti Online users to benefit from the different views of periods stored in the PeriodO data set. One of the major benefits that this would bring would be an increased multi-vocal aspect, which has long been an aim in Digital Archaeology. The hope would be that instead of presenting just Fasti Online's defined periods, different sources' interpretations of the 4D site point could be presented alongside, giving the user a fuller story of the site's interpretation.

The larger boxes in Figure 1 describe in limited detail the metadata which is stored in Fasti Online's database. Each line of data has a date of creation and a creator assigned to it. These creators are distinct from the actors in the green boxes in the lower right portion of the diagram, as they are references to the person entering the data rather than the actors contained in the data set. This is metadata about metadata, which is not presented in the linked data representation, but is incorporated in the fuller model of the data contained in Fasti.

Vocabulary mapping

In addition to the data structure, it was necessary to create mappings for the controlled vocabularies used in Fasti Online. The most important of these is the monument types list. Douglas Tudhope (University of South Wales) used software developed as part of the ARIADNE project to create a rough mapping of the Fasti monument list to the Getty Art and Architecture Thesaurus (AAT) (Paul, n.d.). This built upon many years of work in the challenging field of automatically extracting meaning from archaeological texts (Binding *et al*., 2008; May *et al*., 2015). The 'rough' automated mappings of the Fasti vocabulary were in fact very

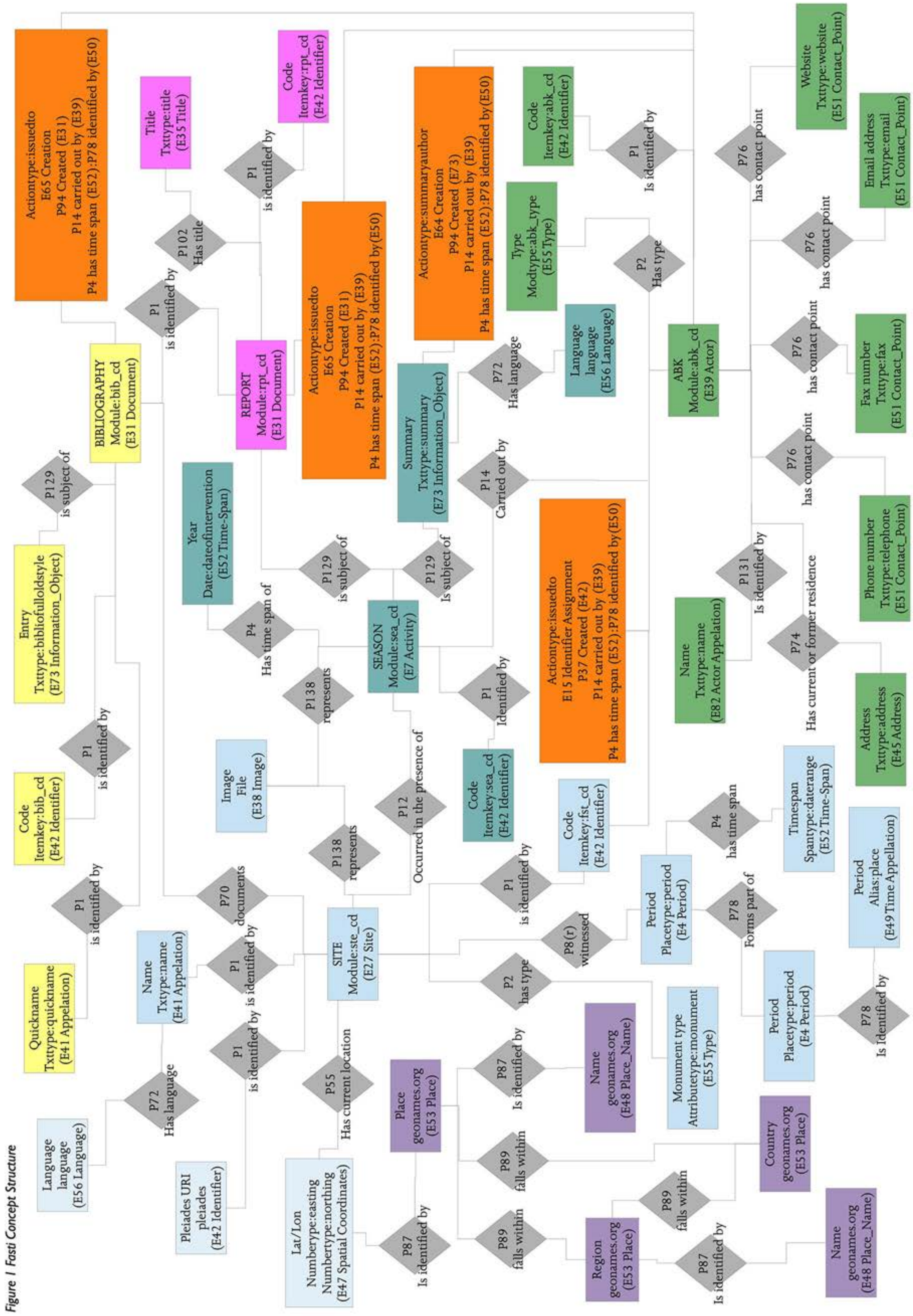

Figure 1. Fasti concept structure.

accurate. The only term that was misidentified was *'Dinosaur Tracks'*, which, although in this case it was discovered in the course of an archaeological investigation, falls outside of the domain of archaeology.

The mappings included a SKOS identification of how strong the relationship was (e.g. http://www.w3.org/2004/02/skos/core#broadMatch). A new administration tool was developed for Fasti Online so that it could hold, display and edit these mappings. This tool is crucial in overcoming the access problems for producing and curating links (Blanke *et al*., 2016). These links are presented in several places in Fasti Online. They are visible and editable in the metadata mapping interface, and are readable on the individual Fasti Online concept pages. Fasti Online also intends to present these mappings on the front end, to help the user understand the terms used. This mapping tool was employed to create further mappings of the Fasti Online data to other vocabularies — such as the Friend Of A Friend (FOAF) ontology (Brickley and Miller, n.d.).

These new links required new URIs to express the Fasti schema and vocabulary in machine readable formats. These URIs took the root (http://www.fastionline.org/concept/) and were expanded with a type and then a leaf (e.g. http://www.fastionline.org/concept/attribute/castle). The raw data type from the Fasti data model is used in the URI rather than a more specific one e.g., 'attribute' rather than 'monument type'. This follows the CIDOC-CRM, where all examples of Fasti Online attributes will be examples of E55 Type. These concepts are then presented as both an HTML document and as a JSON object.

One of the methods suggested by ARIADNE for presenting metadata was the Open Archives Initiative Protocol for Metadata Harvesting (OAI-PMH). Fasti Online used the oai2 php library by Jianfeng Li (Li, 2011). This required writing new classes for interpreting the Fasti Online data that were then used to implement the mappings between Fasti Online and the Ariadne Data Collection Model. In future new classes could be developed to implement the mapping from Fasti Online to the CIDOC-CRM; however the oai2 library was very slow and unstable. The process required a robust OAI-PMH reader which was able to poll the OAI-PMH at regular intervals and collate the responses into a single XML file that included all of the records. This new file could then be served as a response to a query for all records, skipping the resumption token model for software that was not as resilient to dropped connections.

Linked Open Data — is the job done?

Several tasks remain after the end of the project to get Fasti Data harvested by ARIADNE. The OAI-PMH XML files could be generated periodically to allow the data to be accessed more quickly, however, because of the trickle-fed nature of the Fasti Online database, this file would often be out of date. Generating it either on demand or at regular intervals would add processing cost.

Another promising avenue for machine interoperability is SPARQL (Prud'hommeaux and Seaborne, 2013). A standalone SPARQL endpoint using an RDF representation of the Fasti Online data is an appealing prospect. However, this method is likely to run into several of the same problems encountered with the OAI-PMH. This is partly due to the structure of the Fasti Online database being a poor fit for these standalone libraries. It is not optimised to run large dumps of all the data quickly. Extending this for each new technology as it arises is unlikely to be scalable.

The Fasti Online concept pages are currently only available as human readable HTML and JSON. It is a crucial next step that these concepts will be made available as RDF-XML and/or Turtle as well, which are a common standard for presenting metadata triples. These would have to be presented alongside, and made obvious from, the web front end. According to Berners-Lee's open data qualifications, until our URIs resolve to machine readable representations rather than human readable HTML, Fasti is not presenting Linked Open Data (Berners-Lee, 2009).

ARK 2.0 and the Fasti Online API

The foundation for all of these next steps is the Fasti Online API, which was recently developed in order to serve the ARIADNE project. The *Archaeological Recording Kit* (ARK), which Fasti Online uses to manage its database, has a growing library of methods in its API toolkit. The API will most certainly be developed to communicate using a suitable RDF format, and therefore allow us to give new representations for the URI without affecting the other services at Fasti Online.

Fasti Survey

This API was used in a recent project to continue expanding the Fasti Online database. Fasti Survey will be the last part of the Fasti triad of databases, the other components being Fasti Excavation and Fasti Conservation. Developed in collaboration with the KNIR, the Netherlands Institute in Rome, Fasti Survey follows from the *Mediterranean Archaeology GIS* (MAGIS) database of archaeological surveys,[3] whose data was kindly provided by the *Collaboratory for GIS and Mediterranean Archaeology* (CGMA) (Foss and Schindler, 2008). The aim is to register the extent, aims, dates,

[3] http://cgma.depauw.edu/MAGIS/

and techniques of archaeological surveys in Europe and the Mediterranean. This data was in a very different structure to the Fasti Online database, and in order to import it the MAGIS data had to be mapped onto the Fasti database. This was achieved using a python script which read the MAGIS database into a class-based representation. This survey metadata object could then be used to query the Fasti API to insert the new data into the Fasti database. This system was able to use the controlled vocabularies of the Fasti database.

It was also possible to use the API in semi-automated processes. The Fasti API was queried for names which were similar to those in the MAGIS data; the operator could then make a judgement on whether the names matched. This was particularly valuable where there was an inconsistency in the ordering of names, optional initials and varying usage of accents. Supporting information, such as institution, is available through the Fasti API as linked data mapped to the FOAF ontology which made it easy to identify where overlaps in the two data sets occurred. This project demonstrated that a RESTful API could be used for very dynamic communication between two data sets. It is important to be aware of the way in which these technologies shape the way that the data is created and presented. The systems used to create data will always have an impact on the data that is created (Huggett, 2015). Custom solutions like this are likely to give the smallest impact on the data via the process.

Data like those in the Fasti Online database can be represented in many different ways. Allowing data download of the Fasti Online database through an API gives users the flexibility they need to interrogate the data using different software. A popular request is for a spreadsheet table presenting the Fasti data in its entirety. There are many practical problems with this. The normalized tables would need to be loaded into a suitable relational database system and the structure of the database would need to be understood by the user before they could query it with SQL or a similar language. The data could also be presented as a single denormalised table: this would obviously have more redundant data in it, would be slow to generate on demand and would not be easy to query in common spreadsheet software. By exposing an API, so-called power users would be able to download the data in a way that suited their application, either on the fly, or as a single flat dump to their own specification.

Conclusions

Although Fasti Online is not yet part of a fully realised LOD network (Marden *et al*., 2013), it has many avenues available to pursue LOD goals. The continued development of a RESTful API is a fruitful avenue toward achieving these goals. The Fasti Online data is available through an OAI-PMH endpoint, but the current implementation is unstable. Further development of the API will present the data in a practical way. Fasti Online hopes to make more use of the mappings already stored in the database in its front end, for example using the AAT URI to return definitions for monument types in the Fasti Online vocabularies, or making use of alternative period definitions from PeriodO. Mapping these common vocabularies make aggregators such as ARIADNE productive, but also allows us to enrich the Fasti Online data within our own system. LOD relies on pipelines being laid between existing silos, and API provide an extensible way to do this. These are important steps with practical outcomes on the route to the ideal Linked Open Heritage Data ecosystem.

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Mieko Matsumoto and Espen Uleberg (eds) 2018. *CAA2016: Oceans of Data*
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
Oxford: Archaeopress

DOHA — Doha Online Historical Atlas

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Abstract

The Origins of Doha is a research project that aims to explore the foundation and historic growth of Doha, Qatar through a combination of archaeological investigation, historical research and oral testimony. As part of the digital public outreach for the project, Doha Online Historical Atlas (DOHA) was created to disseminate dispersed cultural heritage data. DOHA was developed adhering to Open Standards and using Open Source Software. This paper outlines the application design, architecture and implementation, which has been unique in its nature and scope. Modern web technologies proved to be an excellent platform for heritage data visualization.

Keywords: historical GIS, web mapping, heritage, archaeology, Doha

Introduction

Since 2012, the Origins of Doha Project (University College London — Qatar) has investigated the foundations and historic growth of Doha, Qatar, its transformation to a modern city, and the lives and experiences of its people, through archaeology, history and oral testimony. As part of the digital public outreach for the project, Doha Online Historical Atlas (DOHA), a Historical Geographical Information Science web application has been developed to disseminate the live, multimedia results of Doha's transformation from a pearling town into a modern city. The ultimate aim is to engage the public, specifically the inhabitants of Doha, with their urban heritage, in an accessible and visual manner, by instrumenting memories of place and transformation. In the local context, this engagement may also translate into opportunities for educators within a resource-poor learning environment.

The goal of the paper is to present the design, architecture and implementation of the application.

DOHA was built using Open Source Software and utilises cutting edge web and geospatial technologies. The design allows for the efficient, flexible representation of maps, aerial images, videos, historic records, building recording, and archaeological investigation. This information explored on the web, or on mobile devices that bring the history and archaeology of local places to the user's location. DOHA also incorporates crowd-sourced content both indirectly through geo-located Wikipedia articles and by allowing users to develop content with submissions of historic media and events. The popularity of the application will be evaluated using feedback provided through email, social media sharing buttons and analytic software for web maps that provide insights into user interactions with the map.

Visualization

The DOHA web application has been built with consideration of research in web cartography. Visualization has been described as a process of 'translation of geospatial data into maps' (Kraak, 2001, p. 9). Visualization can be applied to four different approaches, which vary depending upon the purpose of the final map (Kraak and Ormeling, 2003). The approaches are:

- to explore and play with unknown and raw data
- to analyse known data by manipulation
- to access the data behind the maps
- to present the data by specially designed map

The variety of roles played by the maps has been classified in two main categories (DiBiase, 1990):

- 'private visual thinking' — users perform the analysis of their own data

Figure 1. Doha, Qatar.

- 'public visual communication' — the map has a communication function.

MacEachren (1994) introduced the concept of measuring the purpose of the map by using the three-dimensional space of a cube. The purpose of the map changes along the diagonal axis of a cube from private use, which reveals unknown patterns in the data, to presenting known data in the public domain. This approach was adapted also by Kraak and Ormeling (2003). The lower corner of the cube represents maps designed for the public based on known data sets. The opposite corner represents maps used in private to explore raw data (Figure 2).

DOHA was created with focus on broad audiences. The aim was to communicate and synthesize the data in a public domain by using a specially designed map. Thus, the application could be placed in the lower corner of the 'map use cube'. Still, some interaction has been implemented to interrogate the data.

The overall approach in designing DOHA and data visualization was guided by one sentence:

'How do I say what to whom, and is it effective?' (Kraak, 2001, p. 9)

Technology and design

DOHA utilises concepts coined as Web 2.0 and Web Mapping 2.0. The first term refers to an idea of using web in a collaborative, interactive and user–centred way. At the heart of Web 2.0 are applications such as social–networking sites, blogs, wikis or cloud services. The second term is used to describe Web 2.0 applications

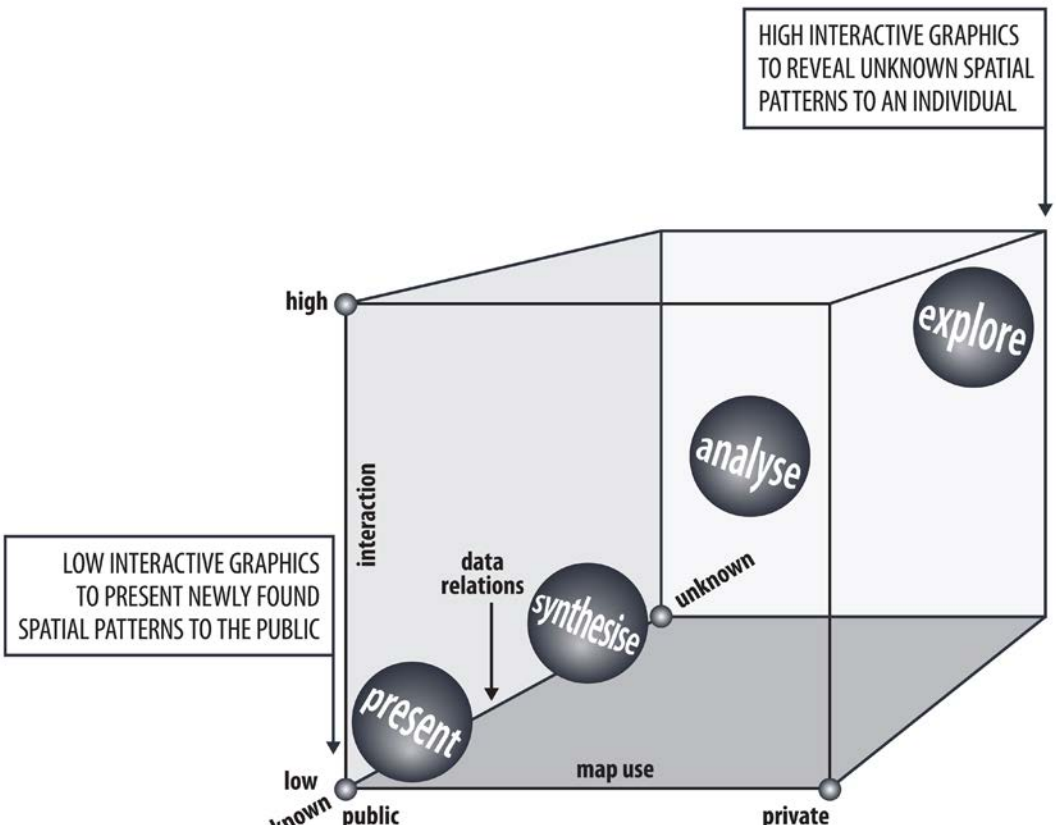

Figure 2. The map use cube proposed by Kraak (2003).

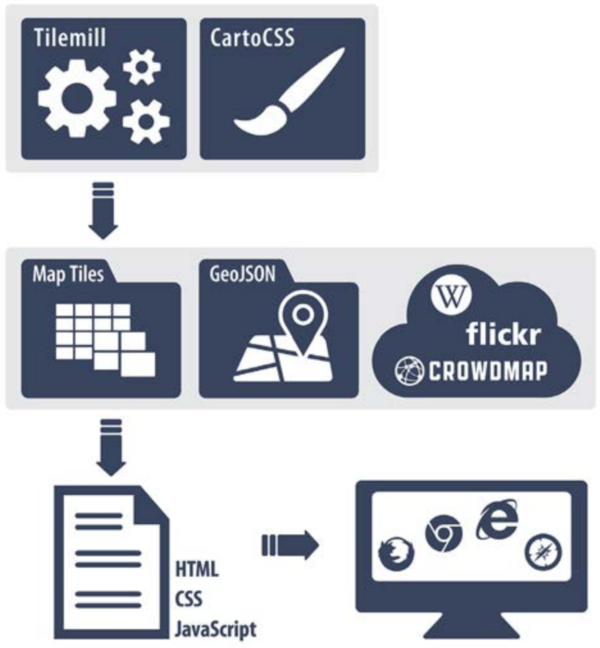

Figure 3. Architecture of DOHA application.

that integrate location information such as GeoTagging, GeoBlogging and Web Mashups (Gartner, 2009).

DOHA is a *mashup* that aggregates services and data from complementary sources using application programming interface (API). *Mashup* combines different technologies and disperse data to produce a new enriched product (Min *et al.*, 2008). DOHA was designed using open source software, allowing flexibility as well as independence from proprietary software (Morgan and Eve, 2012).

DOHA was implemented using HTML, CSS and Leaflet.js API, a JavaScript lightweight library for web mapping. Development of applications using modern web technologies offers great versatility such as responsive design. We are currently working on allowing DOHA to be viewed using many different devices: desktops, tablets and phones.

The selection of web mapping API was coupled with choice of platform and programming language. Other important factors considered were brevity and extensibility of mapping API as well as access to documentation and community support.

Leaflet is 'designed with simplicity, performance and usability in mind' and is being used by sites such as Flickr and Pinterest (Agafonkin, 2016). The use of Leaflet as the client side technology proved to have several advantages. Wide range of plugins developed by third parties provides a quick and flexible way to implement required functionality. The server side of the application was built using server storage space where only static vector and raster files are stored (Figure 3). This implementation does not require additional GIS server software or server-side scripting languages to be installed. The data are handled by the mapping library and are loaded asynchronously to avoid reloading the page. DOHA employs Open Standard formats: Tile Map Service (TMS) and GeoJSON.

Tile Map Service (TMS) is a specification for raster tiled web maps. Web tiles are usually pre-rendered raster images. It is one of the fastest methods of publishing the maps on the Internet because only the tiles needed for current display area are transported through network. These tiles create a 'zoom pyramid' where the number of tiles changes according to the current zoom level. One raster tile usually has a resolution of 256 × 256 pixels and is available in PNG or JPEG formats. The tiles are published using server storage space without installing complex server software.

Web Maps representing Doha's urban development were produced using map design software called TileMill. TileMill can render web tiles and apply visual effects by using CartoCSS stylesheet language. The design resembling vintage maps is inspired by work of Scottish map engravers, printers and publishers, John Bartholomew and Son Ltd (Figure 4).

Implementation

DOHA web application user interface design consists of the map view and a sidebar. The map view relates to the spatial context. The sidebar allows toggling the layers on and off. Users can interact with the features to access more information in a pop-up window.

DOHA currently contains geo-referenced aerial imagery from 1947, 1952 and 1959 and a reconstructed map depicting the city in 1956. Each of the aerial images represents a 'snapshot' of the town at a particular time. The map is the result of a painstaking digitisation process of original surveys conducted in the past. As the research progresses, more stages of city development will be presented in a similar manner.

The web application allows users to overlay historical images on modern maps, such that the historical image can be compared with the present day.

DOHA currently gives access to over 80 geo-tagged Historical Photos, Video Records and Aerial Oblique Imagery (Figure 5). Viewing historical imagery supports community outreach and future research. It also helps 'to understand, connect to or imagine experiences that

Figure 4. Cartographic reconstruction of Doha in the 1950s
(Polygon layer represent settlement growth linked to interactive graph showing population growth. Point layer represents mosques — by dragging orange marker user can query distance to the nearest mosque).

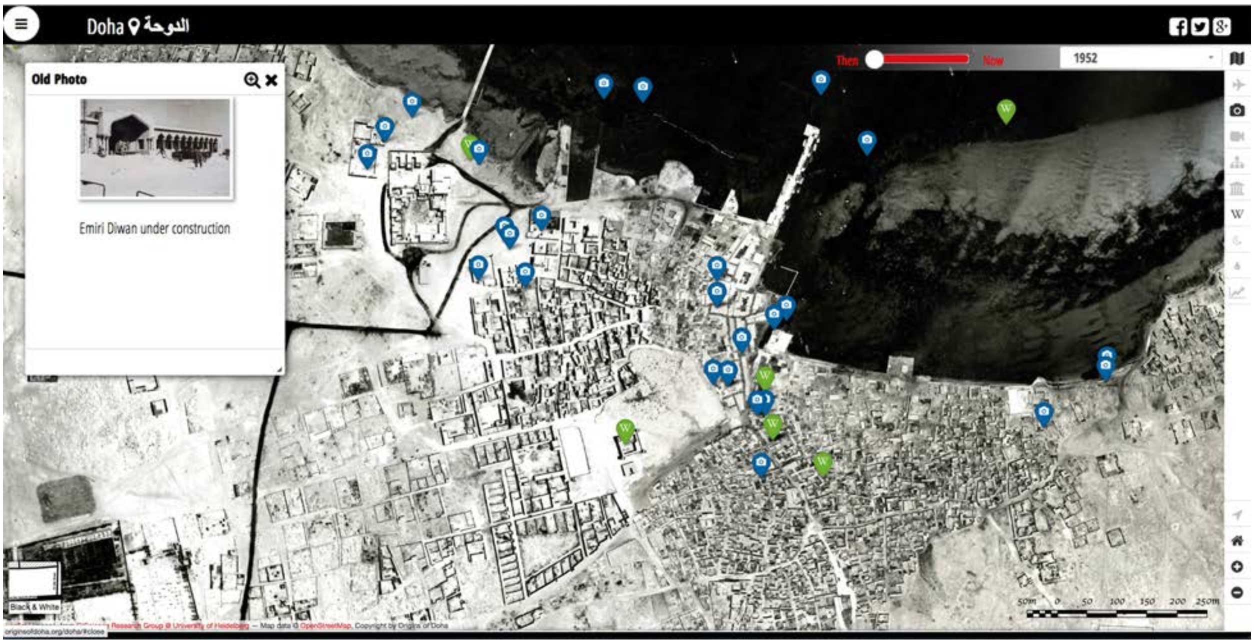

Figure 5. Aerial Photo of Doha from 1952 with overlays showing old photography and Wikipedia entries.

were otherwise remote, either spatially or temporally' (Chew *et al*., 2010, p. 108).

The result of excavations and survey carried out by the project has been represented by Archaeological Sites and Historic Buildings Recording events. When the event is selected, the info- window appears with additional information including a site report, site gallery (from Flickr feed) and site drawings (Figure 6).

DOHA employs Turf.js, a JavaScript library that brings spatial analysis to the browser (Herlocker, 2016). Turf.js allows the carrying out common GIS operations such as buffering, clipping or calculating distance.

Figure 6. Archaeological events represent result of excavations conducted by the project team (User can access field photography, drawings and reports).

Currently the following spatial analyses were implemented:

- calculating the area of a polygon — visualization of districts and population growth
- nearest neighbour analysis — interactive finding nearest mosque
- points density analysis (hexbinning) — aggregation and visualization of wells around Doha

Turf.js paired with Leaflet.js enables development of powerful client-side interactivity usually reserved to server–side technologies.

Citizen science

DOHA plays an important role in Origins of Doha programme of public engagement. The project implemented a variety of strategies to interact with the public such as social media, blogging, school and local events, public conferences as well as reaching out to the press.

The public is encouraged to participate in the project through a variety of channels, and DOHA provides one of them. DOHA engages with the general public by integrating Wikipedia geo-referenced articles and Crowdmap. Wikipedia events are dynamically loaded from web service. Therefore, any changes made to the article are automatically reflected in the application. The aim is to encourage the general public to use Wikipedia as a one of the platforms to enhance DOHA.

Crowdmap is an open-source platform designed by the Ushahidi team. This is a robust platform originally designed to crowd source crisis information (Ushahidi, 2016). Users can share media and information on places and histories in Doha. Crowdmap provides tools and workflow to verify, approve and publish submitted reports. The reports, once approved by the project team, will be integrated with the main DOHA application.

Evaluation

Evaluating the user's satisfaction can be classified as the most important measure of Information Systems success (Xiao and Dasgupta, 2002). End-user satisfaction has been defined as 'the overall affective evaluation an end user has regarding his or her experience related with the information system' (Chin and Lee, 2000, p. 554). The application has been evaluated by using reports on web traffic, performance and user interaction provided by Maptiks as well as user feedback provided via Internet.

Maptiks is novel software that provides insight into user preferences such as areas of map are most looked at, most zoomed or the most often used layers. It is also possible to track various statistics such as the number of map loads of average user activity time (spankgeo, 2016). This valuable information helps to understand how visitors interact with map and to respond by appropriate cartographic and User Interface design (see Figure 7).

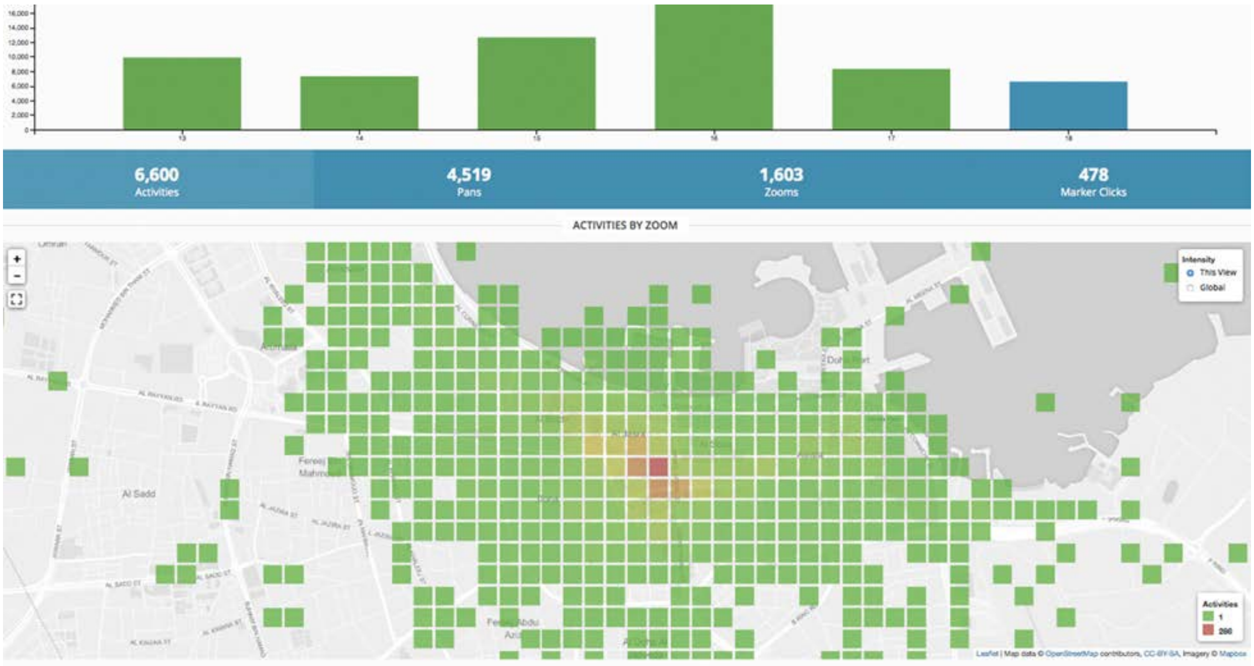

Figure 7. Graphical Interface of Maptiks showing visitors statistics and activity
(Users are particularly interested in old centre of Doha).

User feedback

'What a great little project, takes time to put this stuff together but then it's really interesting for the rest of us.' — user comment under article featuring the application in Doha News (Doha News, 2016)

'Nice history map charting the growth of Doha, the capital of the State of Qatar.' - review by professional blog Maps Mania reporting on Map Mash-ups since 2005 (Google, 2016)

'The thing that struck me most was the detailed and clear description of the technologies and methodologies used, with a clarity that I found exemplary.' — review from a peer archaeologist blog (Marras, 2016)

Conclusion and further work

GIS and Web technologies offer a wide range of possibilities to support the dissemination of heritage data. The use of Open Source Software and Open Standards allow for a flexible design and proved to be very efficient. There are further plans to implement a mobile version of DOHA that will act as augmented reality application with focus on historical photography and aerial imagery and to explore 3D web mapping technologies to visualise architectural research.

The positive feedback from various user groups shows that DOHA web application can be beneficial to the general public as an educative tool as well as to the research community. The developed application provides a strong technical base upon which further spatio-temporal history of Doha can be published. The next stage is to further engage the public and educational professionals in casual browsing, discovery of knowledge and production of user-generated content, through launch activities and publicity work targeted at potential users.

DOHA is available at http://originsofdoha.org/doha/index.html.

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Mieko Matsumoto and Espen Uleberg (eds) 2018. ***CAA2016: Oceans of Data***
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
Oxford: Archaeopress

Digital Archives — More Than Just a Skeuomorph

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Abstract

Historic Environment Scotland curates the National Record of the Historic Environment for Scotland. The record has grown over several decades with an established approach to the long term care and dissemination of documentary archives. We have been collecting digital archives since the early 1990s, but current approaches to describing and sharing digital archives are essentially a skeuomorph of traditional analogue methods — simply an activity at the end of the project or something 'the archive does'. For preservation of digital data to succeed, it requires collaboration between data creators and curators at an early stage. Digital formats offer new opportunities and insights beyond analogue archives and yet traditional approaches hinder the potential for maximising this knowledge. Digital archiving cannot simply mean the continuation of existing archival practices but requires collaboration at an early stage to ensure consistency of approach, to deliver efficiencies and benefits beyond individual projects and make connections across digital collections.

Keywords: archaeological inventories, digital archives, websites

Introduction

Archaeological archives perform an essential, if somewhat undervalued, role in documenting the past. They provide a safe repository for the vast range of information created through research and other fieldwork. In Scotland, planning guidance (Scottish Government, 2011) encourages consideration of the archaeological resource as part of the planning process. The guidance places emphasis on preservation in situ but where this is not possible it encourages recording and/or excavation followed by analysis, publication and archiving of the results. Whatever the merits of 'Preservation by Record' are (cf. Andrews *et al.*, 2000; Hinton, 2013), the approach pre-supposes that archives are preserved for posterity in the first place. For traditional analogue forms of archive, the challenges are well established but for digital formats ensuring long term preservation can be difficult and costly, especially for complex data types. Digital data and media present a series of new challenges to ensure the resources are accessible and reusable long into the future.

About Historic Environment Scotland

Historic Environment Scotland (HES) was formed in 2015 as a new public body bringing together the functions of Historic Scotland and the Royal Commission on the Ancient and Historical Monuments of Scotland (RCAHMS). Our mission is to enhance knowledge and understanding of Scotland's historic environment; to protect, conserve and manage the historic environment for the enjoyment, enrichment and benefit of everyone — now, and in the future; and to share and celebrate our cultural heritage with the world.

HES incorporates the functions, experience and collection of RCAHMS. We are interested in the evidence of human interaction with the landscape of Scotland, including our marine heritage. This remit covers an extremely diverse range of information types. We collect all primary documentary archives relating to archaeological and architectural work undertaken within Scotland and Scottish territorial waters to the 200 nautical mile limit (370.4 km; 230.2 terrestrial miles). For many years the results of our fieldwork were published through the county inventory series. The descriptive accounts illustrated by photographs and measured survey drawings — items of archive that formed the nucleus of our collections. Since the early 1990s we have been actively creating and collecting digital material.

What is a Skeuomorph?

A skeuomorph is a derivative object that retains the ornamental design from structures that were necessary in the original.[1] Examples might include the waste paper bin from Windows or the save icon in Microsoft Word which is an image of a floppy disc. In a digital context arguments in favour of skeuomorphism include that it makes digital devices easier to use for people familiar with the older analogue version being imitated. Arguments against include that it takes up more screen

[1] https://en.wikipedia.org/wiki/Skeuomorph

space on digital devices, and may be more complex and more difficult to learn than a straightforward interface without it.

In this paper we will argue that by replicating the analogue world we are preventing ourselves from realising the full potential of our databases and digital assets.

It is impossible to successfully imitate much about the way we care for paper archives into the digital world. Where in theory you could put a paper report on a shelf and forget about it for 50 or 100 years and still expect to be able to open and read it, the horizon for accessibility of digital archive can be reduced to around seven years.

One of the main challenges is the fast pace at which technology changes and develops, and the nature of that development. Technology changes very quickly and that quick pace of change means that software and hardware can quickly become obsolete and un-useable. This is a problem for anyone engaged in trying to preserve access to digital material.

The nature of development is also problematic. Typically we see a flurry of different software vendors producing their own bespoke versions of a product, with little interoperability between them, before things settle down and standards emerge and/or a particular option becomes dominant. Archaeologists are often enthusiastic early adopters of new technologies, so the problem for organisations such as HES is what to do with the data that is recorded on the obsolete option? For the discarded format there is unlikely to be any updates, and no backward compatibility.

Hardware, software and storage media all suffer from this obsolescence and this is why we need to intervene early in the life of a digital file to ensure that it remains accessible.[2] With paper, considerations of access and preservation could come at the end of the objects journey once it reaches the archive. For digital files decisions taken by the creators of the file at the start of its journey can determine its future accessibility, so both we and our data creators have to work together differently when it comes to digital archives. We need to work together — more and at an earlier stage than we have for paper archives.

To have a good chance of preserving digital information, proper data management has to start at the point of data creation. That data management can include the choice of format in which data is captured and also decisions regarding what metadata are captured at the point of its creation. Proper data management can also be taking time to weed out irrelevant or useless information before it is deposited with an archive. The relationship we now seek between ourselves as the archive and data creators is a life cycle and a partnership.

Investigators consult the existing records we hold to inform the work they undertake in the field; they create records of their work to inform their own understanding and that of the community; and to facilitate the wider community accessing their work they deposit in a central repository.

'Preservation by record' presumes the ability to maintain that record for posterity regardless of format or media.

The nature of archiving digital materials, alongside our limited resources to process them, means that we need to work in partnership with data creators and with other memory organisations responsible for the long term accessibility of archaeological archives.

We simply don't have the resources to manually sort through all the archives that are deposited in an unprepared state. Archives have to be presented in a prepared and controlled fashion, which they often are not. We have to have the support of our depositors to be able to fulfil our responsibilities. Our depositors in turn need a framework in which they can account for the time needed to prepare the documentary material for deposit without this negatively impacting on their ability to win contracts.

Working in partnership

Another way that digital is both facilitating and requiring that we work differently is the way we work with other organisations. Digital preservation is quite difficult and costly, and working in partnership with others can help to achieve economies of scale and the spreading of costs across multiple partners. Digital data, unlike paper records, can be shared and accessed many times and in many locations at once, therefore it facilitates shared working and collaborations.

The Marine Environmental Data and Information Network (MEDIN)[3] is one way in which we seek to achieve this. MEDIN is a network of public and private sector UK organisations working with marine data. It promotes sharing of — and improved access to — that data to all parties and achieves this by working together to establish shared standards and processes. HES is an accredited part of the federated Historic Environment Data Archive Centre together with the Archaeology Data Service and the Royal Commission on the Ancient and Historical Monuments of Wales, as well as potential partners at Historic England and in Northern Ireland.

[2] https://dpconline.org/handbook

[3] http://www.oceannet.org/

Membership helps promote the need for good archival practice for marine data and the MEDIN portal helps signpost our resources to a wider audience.

This is just one example of the way the UK archaeological archive community works hard to try to align our policies and requirements to make depositing archive easier. We also work together in other forums created for this purpose, such as the BEDERN working group[4] of the Digital Preservation Coalition,[5] whose focus is the digital preservation of archaeological archives.

As discussed above, digital preservation can be costly and difficult to achieve (Slats and Verdegem, 2005). Just as we are working together with the archival community, it makes sense that within the heritage sector in Scotland we should do the same. Therefore, rather than each data collecting unit or company trying to achieve this alone, it makes sense for us to have one well equipped centre of excellence for the care, long term preservation, wide dissemination, and accessibility of our data that then links into these other networks. We have always been committed to providing the highest quality of care for our digital collections. Now, as HES, this is protected in statute, requiring us to perform the functions of 'preserving, conserving and developing [our] collections' by the Historic Environment Scotland Act 2014 (Scottish Government, 2014).

Digital archives — who is responsible?

For digital archives each actor in the life cycle of a digital object is responsible for and can influence the longevity of that object. It is vitally important that we demand the highest standards of care from organisations like HES who have a mission to safeguard this information for future generations of users. But the problem is how to be sure that these organisations are delivering on this promise? The digital preservation community has been collectively working for over a decade on this problem. This has resulted in the creation of a European accreditation framework.[6] This framework brings together three important strands of work on the audit and certification of digital repositories, and sets out a path of accreditation which increases in terms of rigour and effort from a self assessment with the Data Seal of Approval up to an external audit using ISO16363 (ISO, 2012). In 2017 CoreTrustSeal Data Repository certification replaced the Data Seal of Approval and World Data System certification of Regular Members.[7]

These are the benchmarks we need to demand of organisations taking in digital records and acting as stewards for this material. HES have been investing heavily in the last few years to prepare for this external recognition of our efforts. Being accredited through this framework of standards helps demonstrate our credentials as a trustworthy repository caring for the data for the sector in Scotland, and therefore encouraging the community to entrust us with their digital assets.

Name	Date established	Purpose
RCAHMS Inventory series	1908	To compile an inventory of the archaeological and architectural heritage of Scotland
Scottish National Buildings Record (SNBR)	1941	Initially established in 1941 to make an emergency record of Scotland's historic architecture during World War II. The SNBR provided an index to archival material associated with buildings.
Ordnance Survey Card Index	1948	To inform selection of antiquities for depiction on Ordnance Survey Maps
RCAHMS aerial survey programme established	1976	To undertake aerial reconnaissance, survey and mapping.
Scottish Industrial Archaeological Survey	1977	To compile a record of Scotland's industrial past
RCAHMS: Maritime Record (sourced from the United Kingdom Hydrographic Office)	1990s	To create a record of marine archaeology
External archaeological archives		Fieldwork archives created by third parties
Architectural Papers		Architectural plans and drawings relating to Scottish architects

Table 1. Key constituent parts of the National Record of the Historic Environment.

The National Record of the Historic Environment

Canmore[8] provides online access to a site inventory of over 350,000 records and an index of over 1.3 million catalogued items, including over 400,000 digital images

[4] http://archaeologydataservice.ac.uk/about/Bedern
[5] http://www.dpconline.org/
[6] http://www.trusteddigitalrepository.eu
[7] https://www.coretrustseal.org

[8] https://canmore.org.uk/

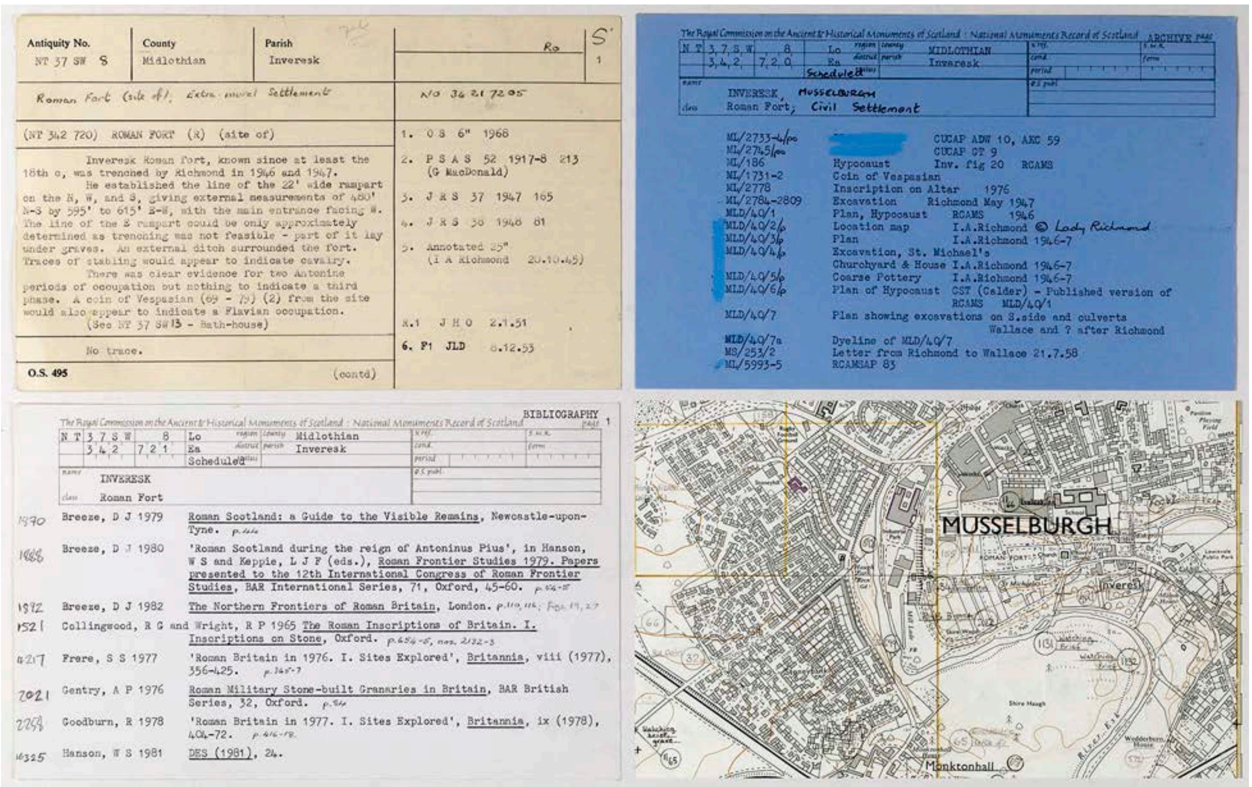

Figure 1. Components of the Ordnance Survey Card Index system for recording sites.

and an ever increasing number of other digital file formats.

Although Canmore is presented as a homogenous resource, the uniformity of the website belies the complex history of the development of the underlying record — explored in more detail elsewhere (Dunbar, 1992). Information held within the record was initially collected by a range of bodies for specific purposes (Table 1).

Gradually these separate resources were incorporated into the holdings of RCAHMS under the auspices of the National Monument Record of Scotland (NMRS) established in 1965. The OS Card Index was transferred to RCAHMS in the early 1980s and maintained and developed to include an index to related Collections material for each site (Figure 1).

The NMRS continued to grow through the Commission's own fieldwork and acquisition programmes. Increasingly, however, more and more of the record originates from external sources. Reports and supporting archives are deposited by archaeological companies undertaking fieldwork, often as part of planning process, whilst the architectural collections continue to grow through the deposition of material from Scottish Architectural Practices and architectural historians.

Since 1998, the record has been published online through Canmore and from 2004, PastMap,[9] which also provides access to formally designated datasets (Scheduled Monuments, Listed Buildings, Gardens and Designed Landscapes, The Battlefields Register, etc.), and most Scottish local authority Historic Environment Records.

Increasingly the record provides more than just a reference evidence base. Through Canmore and PastMap, the record provides access to knowledge, inspiring research and engaging interest in the past, and encouraging appreciation of the historic environment. Innovative projects like MyCanmore,[10] Scotland's Rural Past[11] and Scotland's Urban Past[12] encourage a participatory approach enabling individuals and community groups to contribute information and images directly to the national record. In turn, the participative process helps build the evidence base documenting Scotland's past.

With the continued growth of the collections and development of Geographic Information Systems enabling the seamless mapping of archaeological

[9] http://pastmap.org.uk
[10] https://canmore.org.uk/contributions
[11] http://www.scotlandsruralpast.org.uk/
[12] https://scotlandsurbanpast.org.uk/

sites across the landscape and historic landuse assessment,[13] the record now provides much more than a monuments record. The strength of the record lies, not in the individual records but in the accumulation of knowledge from a range of sources, gathered from a range of different purposes. Whilst referencing the structure of the card index, the move from paper to online digital records has provided a catalyst for change. Online digital access has driven forward better knowledge organisation, improved functionality, presentation of and interaction with, the record.

Database developments 1992 to 2016

Initial transfer

Information held on the Ordnance Survey card Index (Figure 1) was first computerised in the 1980s and stored in a STAIRS database. The data was migrated to Oracle Forms in 1990 and this software has provided a stable platform over the last 25 years (Thomas and McKeague, 2013).

By 1992, the database comprised four main tables (instead of the three distinct elements to the card index) with additional look-up tables and authority lists:

- *'Main' table:* recording site location and classification data
- *Archaeological / Architectural notes:* holding the descriptive accounts for each site.
- *Bibliographic references:* The database provided a searchable index to sites with links to related items in our
- *Collections:* provided an index to and documentation for drawings, manuscripts, photographs etc.

In the absence of a GIS, site locations continued to be marked on the accompanying OS 1:10,000 scale map sheet.

These early iterations of the database tables essentially imitated the component parts of the OS card index. The structure supported established recording practices and providing a familiar recording environment reflecting the simple structure of the Card Index, albeit in a digital context. As an internal data management tool the database was sufficient for existing needs. However, in simply replicating the Card Index in a digital format the potential of the data was not being realised, particularly once the content was published online. Moreover, as the content grew (both in number of sites and collection items held) and data standards developed, the limitations of the existing structure as simply a monuments index became more and more apparent.

Over the last 25 years, database developments have been driven by the digital revolution. Growth has been organic and often responsive, driven forward through organisational and project requirements and the need to provide rich content online.

There have been a number of significant changes to the database structure, from the adoption of controlled terminologies to the introduction of an Events module to document activities about sites more effectively, and collection hierarchies to adhere to the ISAD(G) standard,[14] and index our Collections more effectively.

Site classifications

On the Card index, sites classifications were simply listed as series of terms. This approach was replicated on transfer to the database, retaining the classifications as a series of non-controlled values in a single field held on the 'Main' table. However, once published on Canmore the limitations of a non-controlled vocabulary greatly hindered the ability of the public to search the record effectively.

The solution was to adopt a thesaurus model (from that in use at English Heritage — now Historic England) to provide controlled terminologies, eliminate typographical errors and improve information retrieval. As records were often classified with more than one term, a separate table was introduced storing the site classifications in a one-to-many relationship to the locational detail in the Main table.

From Archaeological notes to Event recording

The Card Index provided a 'biography' for each site usually comprising a copy of the published inventory description or a summary account of the site compiled by an Ordnance Survey recorder from available sources. This initial account may be augmented by additional descriptions often provided by Ordnance Survey field investigators, or from summary accounts of excavations reported in national or local journals, or the annual summary of fieldwork in Scotland: *Discovery and Excavation in Scotland.* The relevant sources were listed against each block of text on the Card Index.

When the information on the cards was digitised, the descriptive accounts for each site, often comprising several distinct sets of observations, were simply stored as a single monolithic block of free text in an associated notes table. New information would simply be entered at the end of the existing text — in some cases creating very large unstructured records.

[13] http://hlamap.org.uk

[14] http://www.icacds.org.uk/eng/standards.htm

With both the growth in fieldwork and the numbers of actors undertaking fieldwork, and acknowledging the development of the 'Events-Monuments-Archives' model from the late 1990s, an Events module was added to the database in 2007. Existing descriptions were migrated to the new table and stored as 'notes', but any new fieldwork undertaken was assigned its own Event record. Adoption of an Events thesaurus as well as controlled pick-lists for the relevant people and organisations involved improved indexing of the descriptive accounts.

Collections table developments

For many staff, the Card index simply provided a list of any collection items associated with a particular site. There was limited scope to note additional information. Once in Oracle, the potential to manage the Collection more effectively was realised. Gradually fields to record more detailed information relevant to the item were added. Major cataloguing projects in the 1990s, including the Scottish Architectural Papers Preservation Project (RCAHMS, 2004), exposed the limited functionality of the flat file structure inherited from the Card Index. Although collection records could be linked to the relevant sites it was not possible to create associations within the Collection: to link all records relating to an architectural project or practice or to an archaeological excavation.

Defining the hierarchical relationship formalised the relationships between items in the collection and their parent collections in accordance with accepted archival practices (Figure 2). Adopting the International Standard Archival Description (general) [ISAD(G)] provided the structure to achieve this. The hierarchical model facilitates description at a number of different levels. This allows us to account for the complexity of an archive which might require description at increasingly granular levels. For example, we might begin with a description of an archaeological company, and proceed through levels of geographical region, and then project, then category of material, down to an individual item such as a report or photograph.

Actors

As a monuments record, emphasis has always been placed on the location and classifications of the records with the authorities responsible for the identification or field visit noted as part of the free text. Introduced to assist with the cataloguing of Collections items, the People and Organisation tables also help document the event record explicitly.

Changes in the database structure

The structure of the oracle database has evolved from simply replicating the Card Index to become a complex relational database embracing the possibilities of the medium beyond a simple skeuomorph of the original analogue record. Enhancements are designed to improve the organisation and indexing of information within the database and drive, or are largely driven by the need to improve the user experience of the record.

Evolution of online access

As a website, Canmore needs to provide user friendly searches across the underlying complex relational database tables. The user can quickly find and retrieve information about a site, see how many collection items are associated with that site, and browse associated digital images. Re-launched in May 2015 with significantly improved searches across our collections, Canmore consumes customised web services from the underlying database to present information to the public.

Since its launch in 1998, Canmore has undergone significant evolution in both design and functionality with major design overhauls on the centenary of RCAHMS in 2008 and again in 2015 (Figure 3).

The website is essentially a wrapper, or shell, presenting information from the database in an easily readable format. Whilst there may be merit in preserving the earlier versions of Canmore for posterity, there are limitations to what can be preserved beyond screenshots and the design requirements. Programming languages and software evolve or change. With each iteration of Canmore the web services are redesigned, refined and repurposed to serve the new website, so the long term preservation of previous versions will only maintain the wrapper, and not the functionality of the website.

With a proposed redevelopment of the underlying database, Canmore will undoubtedly undergo further redesign with the web services repurposed to take advantages of improved indexing of the data. The data itself is maintained and backed up within the Oracle database and is not archived.

More than an archive

Most users will think of Canmore as an archive providing access to a range of drawings, images and written accounts indexed by location, site classification and increasingly by named collections. Yet the value of the National Record for the Historic Environment is much more than the individual holdings; the true worth lies in the temporal and spatial relationships between items. Pursuit of the website as the solution

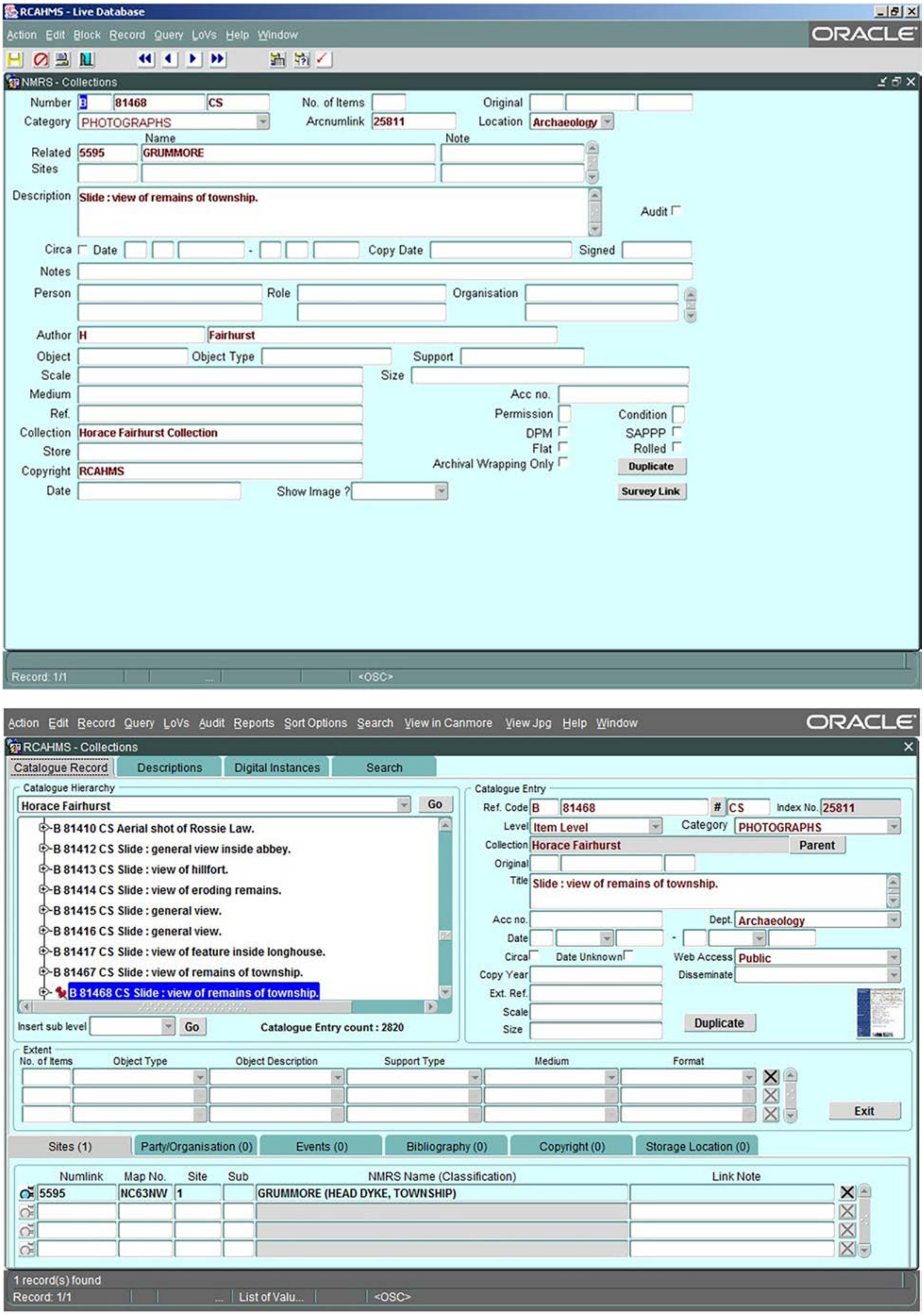

Figure 2. The database tables have evolved over the last 25 years. In the illustrated example the Collections form has evolved from a simple flat table (upper) to a complex hierarchical structure (lower) enabling more sophisticated indexing of data.

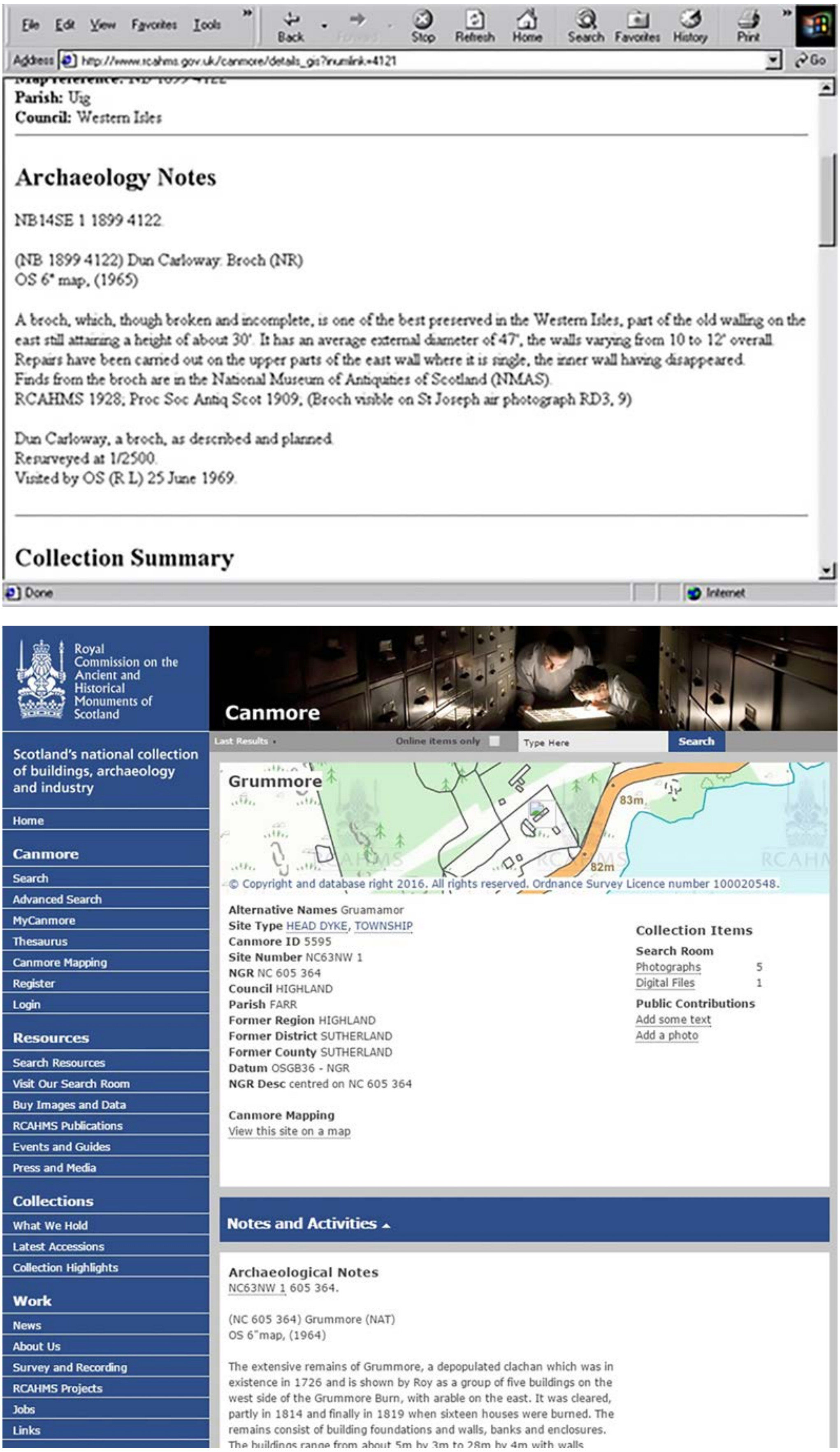

Figure 3. Since 1998 Canmore has been redesigned in 2008 and again in 2015. The upper screenshot on the shows the original design of the website and that on the lower shows the redesign from 2008. The current design may be viewed online (for instance https://canmore.org.uk/site/61704).

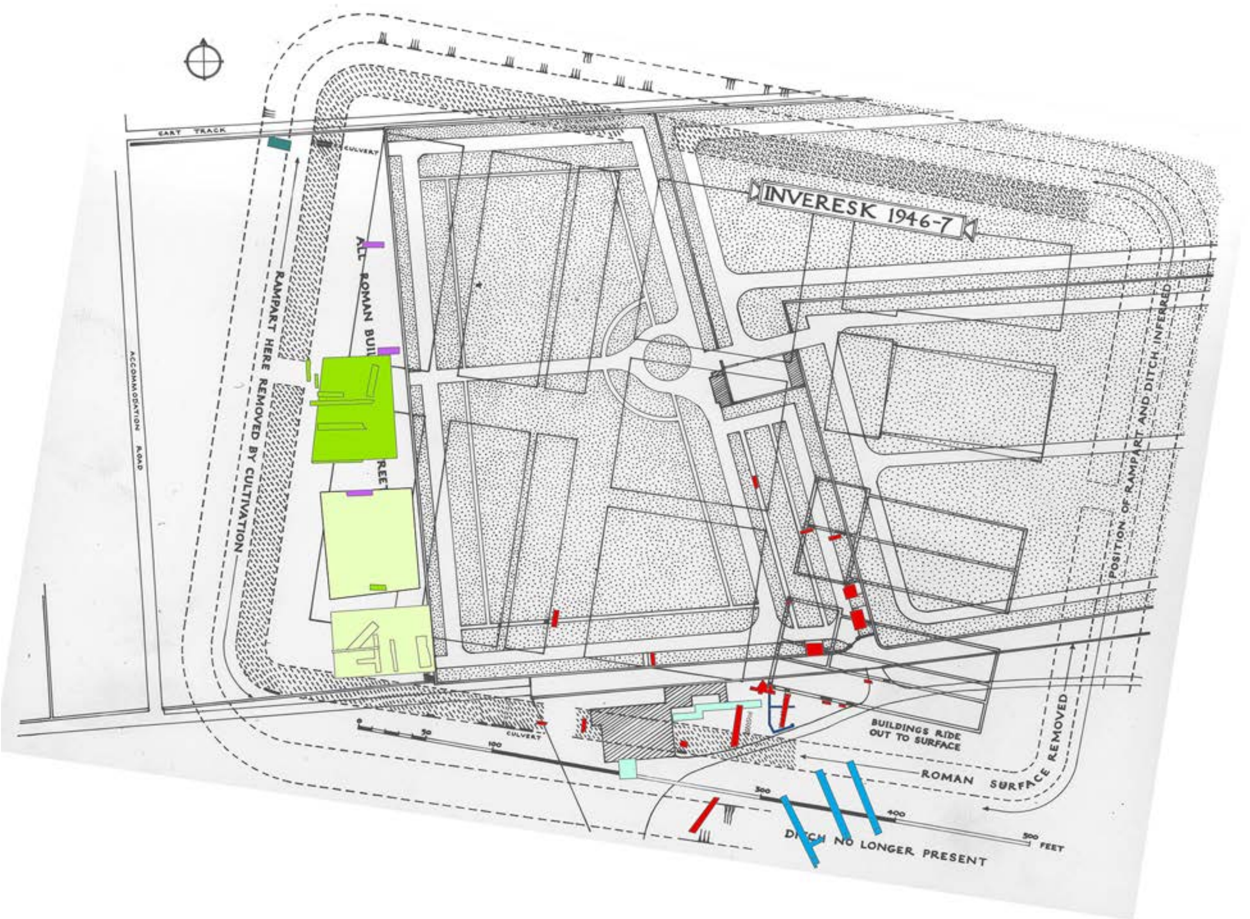

Figure 4. The sequence of excavation trenches superimposed on a geo-rectified copy of Sir Ian Richmond's plan of Inveresk Roman Fort (SC 351350) (Copyright Historic Environment Scotland). Richmond's trenches are shaded in black, later interventions are in colour.

for publishing catalogues and data online ultimately stagnates or fossilises the potential digital data offers beyond the analogue records. The following case studies consider the need to think beyond the structures of the archive to help realise the potential of digital data.

Spatial knowledge

The Canmore record for Inveresk Roman Fort, Musselburgh, East Lothian,[15] has extensive archaeological descriptions built up over many years, with an associated index to related catalogued material. At the time of writing, the Canmore record provided an index to 177 prints and drawings, 26 manuscripts, 2 digital files and 4 miscellaneous items as well as presenting online 9 low resolution copies of digital images from the archive. In the next few years the index will grow with the accessioning and cataloguing of material from more recent investigations at the Roman Fort.

Although the organisation of information has matured and the functionality of searches has increased online, Canmore largely replicates the familiarity and limitations of the card Index without fully acknowledging the accumulative knowledge within each record. Within the holdings for Inveresk there is a reconstructed ground plan of the fort,[16] established following excavations in 1946 and 1947 (Richmond, 1981). This is in addition to several more recent excavation reports — each containing a trench location plan locked within the report. Each report may be consulted individually, but the cumulative value of the knowledge therein is not being realised. The value lies not in the individual item but with the overall understanding of the resource both in the context of the site and in its wider landscape; in this case the adjacent *vicus* or civilian settlement around the fort and associated field-systems to the south–east. Capturing the extents of individual interventions, and even the individual features recorded within the excavations in a GIS helps fulfil the requirements of a modern inventory or archaeological record to form the evidence base for protection, site management and interpretation (Figure 4). For digital data this information is either captured

[15] https://canmore.org.uk/site/53919

[16] https://canmore.org.uk/collection/351350

electronically in the field through high precision GPS or created through design software in the office, leaving the residue of legacy data to be captured. Yet the value of born digital spatial data cannot be realised if it is treated as just another archive item and catalogued as part of the collections associated with a site spatial record. Digital spatial data needs to be collated and presented spatially through GIS layers, Web Map and Web Feature Services. To do so requires adoption of standards and the infrastructure and resources to manage and publish the data.

Open Data

Publication of the G8 Open Data Charter (Cabinet Office, 2013), and the subsequent release of national Open Data Strategies including the *Open Data Strategy* for Scotland (Scottish Government, 2015), recognises the potential accessible data offers to deliver more efficient and effective government and business, and to drive innovation. Adopting an Open Data approach for archaeological archives has the potential to radically change how that data can be used, impacting on traditional forms of publication.

Traditional excavation reports contain a synthesis of the results based on the detailed description of a site's stratigraphy — supported by specialist reports containing or referring to detailed structured data which may also be deposited in archives as paper records or digitally as pdfs or in other proprietary data formats. The depth of detail places a burden on the publication both in terms of content and cost of production and a significant cost to the reader. One solution to address both the costs of publication and the backlog of reports awaiting publication is to publish solely online, usually in pdf format. For instance, in addition to the synthesis of excavations, many reports contain specialist reports on a range of artefactual material and scientific studies, including animal bone, pollen analysis, plant remains, molluscs, and fauna. The value of specialist data is restricted by the print format (or in the case of pdf two star Open Data) and cannot be easily extracted, reused and analysed against similar datasets from other publications. As demonstrated by the LEAP Project (Richards *et al*., 2011), electronic publication offers the possibility to drill down from the broad synthesis to the detail within four case studies. Moreover, electronic publication enables the reader to escape from the linearity enforced by printed reports to support a layered presentation (Clarke, 2001, p. 352).

Publication of Data Papers in journals like the Journal of Open Archaeological Data[17] or Internet Archaeology[18] signals a new approach to data, providing a link between the evidence and the synthesis. The approach is predicated on preservation of the data in an appropriate archive and open access to encourage reuse.

In encouraging Open Data these journals are in the vanguard of a more collaborative approach. As with the spatial dataset from the GIS, the value of a specialist report can be enhanced in comparison with similar datasets from other relevant projects to allow comparisons to be made, data to be reanalysed and tested and considered as part of a landscape. This approach is exemplified by analysis of radiocarbon dates at a national and international level, where the knowledge developed from considering the context of individual dates in a wider landscape has offered significant new insights into prehistoric Europe (Whittle *et al*., 2011; Manning *et al*., 2016).

A further challenge is the demand for Linked Open Data both in terms of items within the Collections and the tabulated information, including event descriptions, within the database tables. For the latter mapping fields to the CIDOC-CRM offers an opportunity to publish selected extracts of the data. Development of the database from the late 1990s has introduced greater rigour through controlled terminologies, enhanced indexing of descriptive accounts and applying controlled values for the People and Organisations associated with each record. This work in itself will not lead to publishing Canmore as Linked Open Data but provides the foundation from which to publish extracts of the database mapped to the CIDOC-CRM.

Summary

In reviewing the development of Canmore as a sophisticated online resource, this paper considered the origins of the record in the Card index developed by the Ordnance Survey and its migration into an oracle database essentially as a skeuomorph of the analogue approach. The limitations of a Card index were quickly exposed through the database and, particularly with online publication through Canmore, the need to enhance indexing and information organisation as well as manage digital objects in the database have driven developments and innovation forward. And yet the very success of web catalogues as an indexes to data and collections are in themselves skeuomorphs of analogue catalogues. By necessity they are object, project or site focused and as such cannot acknowledge the need for innovative approaches to maximise the value of data collected. To do so, the sector needs to think holistically and work collaboratively from data collection through to publication outside the traditional silos to develop interoperable resources.

[17] http://openarchaeologydata.metajnl.com/
[18] http://intarch.ac.uk/

Data creators need to become more aware of the challenges of long term curation of digital data and demand more from organisations acting as repositories and custodians for future generations in order to achieve preservation by record. We need to ensure that digital archives are adhering to the existing framework of international standards for digital preservation and that they are properly resourced to do so. Archives need the support of depositors to be able to fulfil these responsibilities. Data creators in turn need a framework in which they can account for the time needed to prepare the documentary material for deposit without this impacting negatively on their ability to win contracts.

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When Data Meets the Enterprise: How Flanders Heritage Agency Turned a Merger of Organisations into a Confluence of Information

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Abstract

In 2012 Flanders Heritage Agency was created as a central agency dealing with immovable cultural heritage — broadly defined as archaeology, architectural heritage and cultural landscapes — in Flanders. Prior to this, tasks of this agency were carried out by several independent agencies. The merger created a very heterogeneous set of business processes, IT-components and systems. Together with new heritage legislation, this prompted a re-evaluation of these systems.

This paper will delve into our system architecture, built on a core separation of concerns between data-driven and process-driven applications. The resource oriented focus of REST services has served us well in creating datasets interlinked through URIs. From there it's only a small step to publishing the data through semantic technologies such as RDF and linking it with other, external, data sources.

Keywords: enterprise architecture, web services, linked data, open data, URI

The winds of change

The Flanders Heritage Agency (FHA) was created in 2012 as an agency of the Flemish Government that deals with immovable cultural heritage: broadly defined as archaeological heritage, architectural heritage and cultural landscapes. The main responsibilities of this agency are to maintain inventories of and protect heritage, to support the management and conservation of this heritage, to help define the policies surrounding this heritage, to conduct research about the effect of these policies, and to disseminate information about this heritage and the relevant policies. To this end it interacts with several different stakeholders: heritage owners, the general public, other Flemish government agencies, local governments, spatial planners, heritage professionals, etc.

Before 2012 these responsibilities were already a task of the Flemish Government, but they were carried out by different agencies (Figure 1). The main participants were called the Flemish Heritage Institute and Ruimte en Erfgoed. While both dealt with all types of immovable cultural heritage, the first mainly focused on heritage research (inventories, excavations, etc.) while the second handled the management, and conservation aspects and tasks such as excavation permits. Further back in history, 2004, two different organisations existed. At that time, the division was mainly about the type of cultural heritage they dealt with. The Monuments and Landscapes Agency handled all matters concerning architectural heritage and cultural landscapes; the Institute for Archaeological Heritage, handled archaeological matters.

These organisational changes have had an important impact upon the kinds of data that need to be recorded and the information systems used to record them. Every change has been a disruptive event that challenges existing opinions and offers opportunities for growth and innovation. We have previously detailed (Van Daele *et al*., 2016) how this has affected the users of a single system (the heritage inventory). This paper is more concerned with the resulting overarching systems architecture that allows heterogeneous processes to interact in a sustainable way.

Since the creation of the Flanders Heritage Agency, other events have transpired that have been instrumental in defining the current state of information systems within the agency. First, and foremost, in 2013 new heritage legislation was voted in. This legislation is the first ever unified legislation for archaeology, architectural heritage and cultural landscapes. In 2015 it came into full effect, although most of the legislation concerning archaeology took until 2016 to be fully implemented. While the new heritage legislation built upon the preceding instruments, it also created new responsibilities and tasks for the agency, especially where archaeological heritage was concerned. De Roo, De Maeyer and Bourgeois (2015) offers a more in-depth analysis of the new legislation, although certain aspects have changed somewhat since then.

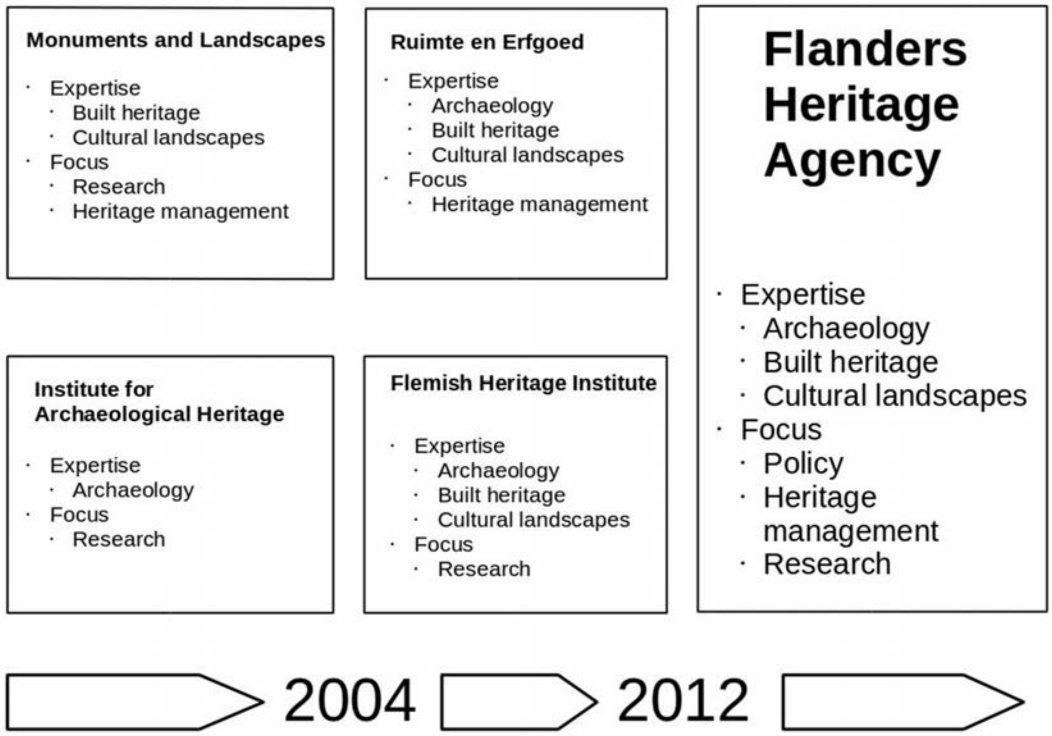

Figure 1. Evolution of heritage organisation in Flanders in the 21st century.

Other policy decisions of the Flemish Government have also had an impact. In 2015 a policy concerning open data was adopted. This stipulated that most government data should be available as open data under one of several possible licenses (Vlaamse Overheid, 2016). In the same year a special program of the Flemish Government called 'Radicaal Digitaal' was launched (Vlaamse Overheid, 2015). This project aims to digitise as many interactions as possible between citizens and their government by 2020.

A new beginning

When the Flanders Heritage Agency was created in 2012, it found itself the inheritor of two very different IT-environments. The differences in focus of the two previous agencies were very obvious both in the kind of data that was generally collected, curated and published and in the technologies used in building the systems to hold and process this data.

One agency, Ruimte en Erfgoed, dealt with both spatial planning and management of heritage. Its focus lay more with the heritage as a part of the spatial planning process, than with the heritage itself. Most of its work was process and workflow driven. There were applications for case-management such as requesting an excavation permit, a restoration grant or permission to modify a listed building. Most of the systems created by this organisation were inward facing. They were built by the agency for use by its own staff to help them carry out their work as efficiently as possible. Almost everything was done in one giant, rather old, case-management system. This system had originally been built for spatial planning, but afterwards heritage workflows had been integrated in the system. Since the system was not built with specific heritage purposes in mind, this was never an easy fit. Technologically speaking the organisation was mostly organised around proprietary software. Software was written in .Net or Java, generally with Oracle or SQL Server databases and Windows servers.

The second agency, the Flemish Heritage Institute, was an agency that mostly dealt with research on cultural heritage. Its work was much more data-driven. It carried out excavations, maintained a library, a depot and an archive and created heritage inventories. Since the latter were the focus of a lot of other processes, they received a good deal of attention. Although the inventories were created by the institute they were readily shared with the world through websites and databases. Most of them were located in a single inventory management system (Van Daele *et al.*, 2016) that, while not as old as the case management system, by 2012 had received several major updates expanding the capabilities and complexity of the system. It was felt that it did too many things at once since the system also contained actors, events, images and thesauri. Technologically speaking the Flanders Heritage

Institute was favouring FOSS (Free and Open Source Software) and *nix (Unix or Linux) systems, using PHP as the main programming language and PostgreSQL and MySQL as the main database servers.

Fairly quickly after the merger, a decision was made regarding the technological stacks. The new agency adopted the preference for FOSS of the Flanders Heritage Institute. As can be evidenced from a study about the adoption of FOSS by the Flemish Government (Ven and De Bruyn, 2011), several factors can contribute to such a decision. For the FHA the reduced license costs were important, but not the only factor. Prior internal knowledge, the avoidance of vendor lock-in, the presence of boundary spanners and general ideology all played a part as well. For the servers of the new agency, the *nix and PostgreSQL technologies of the Flanders Heritage Institute were retained. The programming language of choice became Python. It's a good general purpose language, well-suited to the web and with a healthy support for GISwork. Contacts at the time between the Flanders Heritage Agency and the Getty Conservation Institute concerning the Arches project (Myers *et al.*, 2016) certainly played a part as well.

A new enterprise architecture design emerged as well. The focus was shifted from building a few big, monolithic systems toward building many smaller systems and integrating them. Such a Service Oriented Architecture (SOA) is very much focussed upon the interactions between the different systems. It's essential to define the service contracts i.e. the questions a service should be able to answer, rather than the service implementations i.e. where the service should get the answers from.

Types of applications

Within the new enterprise application architecture there is a distinction between the two types of applications (Flanders Heritage Agency, 2016a). This corresponds to the dichotomy between data-driven and process-driven. We refer to the first type as *Authoritative Sources*. An authoritative source is the one and only source for a certain piece of information. Its data should always be referenced, never copied. The data in these systems is very long-lived or even permanent. Its relevance does not greatly diminish by age. Queries done in these kinds of systems are very much about the data itself, e.g. 'List all sites that have a Gothic church'. Within the authoritative sources a further distinction can be made between primary and secondary sources. The primary sources are our core-business, such as heritage inventories or the register of accidental archaeological finds. The secondary sources support the primary ones, but are not our core-business. Some of them are not even maintained by Flanders Heritage. A prime example would be thesauri and controlled vocabularies. They are essential for querying the primary systems, but they are a means, not an end.

A typical authoritative source would be the decrees authoritative source.[1] This source contains legal documents that designate or alter the designation of heritage objects. In essence the source captures what type of decision was made, by what responsible entity, at what point in time and the documents that make that decision binding. Whenever an application needs to reference a decree, it refers to this authoritative source. The authoritative source itself refers to other authoritative sources where necessary, such as thesauri or an authoritative source of actors and agents involved in our information systems.

The second type of applications we refer to as *Process applications*. These applications guide one or more (internal or external) users through a business process. The applications and the queries executed are mostly concerned with the workflow, e.g. 'List all requests for an excavation permit that have to be handled within the next 5 business days'. Quite a lot of the data in these systems is of a more temporary nature than with the authoritative sources. While we distinguish these types of applications from the authoritative sources, they are actually closely integrated with them since the process application reads from and writes to several different authoritative sources.

A typical process application would be our Accidental Finds Process Application (Figure 2). All accidental archaeological finds by the general public need to be reported to FHA through an online form. Whenever such a report is filed, a workflow is started. This process-application keeps track of scheduling (every report needs to be handled in a certain amount of time) and parties involved (using the actors authoritative source). It tracks communications between FHA and the reporter (stored in the Mail authoritative source) and interacts with several GIS services and an external authoritative source for address data (CRAB) to provide location information. Sometimes the archaeologist handling the report decides a small excavation is necessary. In such a case, an excavation permit is automatically generated in the authoritative source for excavation permits. The process application offers our archaeologists, responsible for tracking this business process, an easy and intuitive interface by interacting with a lot of different authoritative sources.

Apart from the two types of applications we also maintain several different *components*. These are pieces of software that are not intended to be used as stand-alone applications, but as modular building blocks

[1] https://besluiten.onroerenderfgoed.be

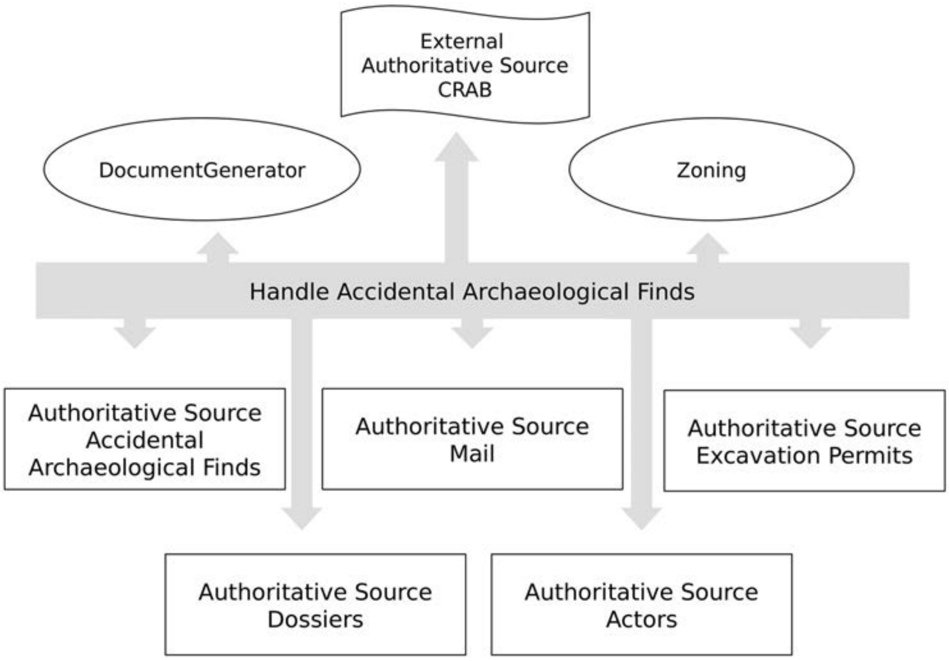

Figure 2. Handling reported accidental archaeological finds through the process application.

that help create authoritative sources or process applications. Not all of them have a user interface. One example is the DocumentGenerator. This service generates pdf documents based on a certain template and data sent to it. Our process-applications rely heavily on this service for generating the communications with other parties. This component has no user interface of its own. In contrast, a component that is all about the user interface would be our Zoning component. This is a Javascript module that allows a user to create a geometry by interacting with various services and components. In one application this is used to record the boundaries of an excavation report. In another, it is used to record the boundaries of a spatial planning application. The component itself does nothing more than interact with lots of different services and present results to the user. But it relies upon the application in which it is embedded to actually store the geometry it captures for the user.

Resource Oriented Architecture

When building a SOA, a key decision has to be made regarding the type of services to implement. Two main types of services exist. The first, Remote Procedure Call (RPC), consists of calling remote services that act similar to a function in a programming language. This style is exemplified by technologies such as SOAP and XML-RPC. A well know example would be the WMS or WFS GIS services. In recent years this type of service has become less popular and is often being replaced by Resource Oriented Architectures, exemplified by the REST paradigm (Fielding, 2000; Webber *et al*., 2010). In this paradigm, *everything* is a resource. Where RPC services focus on the actions to be undertaken, REST has a clear focus on the resource upon which the action is undertaken. The Flanders Heritage enterprise architecture is based heavily upon the REST paradigm. But we keep employing RPC services where deemed necessary and more suitable, such as the aforementioned WMS and WFS services. Within both RPC and REST services, the exchange format can be either XML or JSON. Within Flanders Heritage, JSON is the preferred format, mainly because it is very lightweight, taking up less bandwidth than a similar XML document and very easy to interact with for humans. Our services have become cornerstones of the new systems and the principal means for our own User Interfaces (mostly so-called Single Page Javascript applications) to interact with our data. This ensures that all services are thoroughly tested and used on a regular basis.

We define a resource as any information object we wish to describe. This can be tangible such as an object in a heritage inventory, a report or a person, or something less tangible such as an event or a decision. Every resource is uniquely identifiable by a Uniform Resource Identifier and is addressable on the World Wide Web through the HTTP protocol. A set of rules and guidelines (Flanders Heritage Agency, 2016b) was created for what is and what is not a good URI within our architecture. The first rule is that a URI should always identify a resource, never an action. The action to be undertaken should be coded by using the typical HTTP methods (GET, POST, PUT, DELETE). A URI such as https://

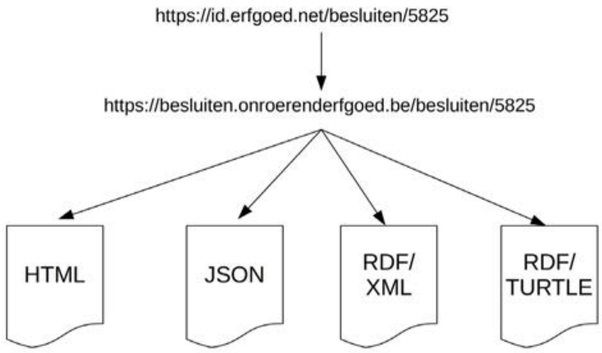

Figure 3. Redirecting from a resource URI to a document URI and serving different representation of this document through content-negotiation.

besluiten.onroerenderfgoed.be/besluiten/addNew.py is not allowed and should be POST https://besluiten.onroerenderfgoed.be/besluiten. A second very important rule is that a URI should be as meaningless as possible. Anything more than a very general resource type and some kind of identifier within that type is generally frowned upon. In the past we have observed a tendency to insert meaning into URIs, such as including a community name in the URI for a heritage object. This becomes problematic after a while when the community's name changes or when it turns out it was spelt incorrectly to begin with. This then leads to confusion because the heritage object is in a different community than that which its URI announces. Or the URI is changed to reflect the new situation, leading to broken links unless a careful redirect scheme is in place. Therefore, our URIs generally look like *https://id.erfgoed.net/<resourcetype>/<id>.* Other, more cosmetic, guidelines were put in place to remove anything technology specific from a URI (such as the .py suffix) and to always use plural style resource names.

Following the Cool URIs specification (Ayers and Völkel, 2008), we make a distinction between a URI for a resource or information object (e.g. an archaeological site) and a URI for the document about that object (e.g. a webpage about that site). The resource URI identifies a more abstract concept, the document URI a description of that concept. While we find this distinction to be relevant, it also allows us to keep our resource URIs very stable. We wanted to ensure that our resource identifiers were as permanent as possible. Our organisation name, and the corresponding domain name, has changed a few times in the past, and we foresee this might happen again. While there are other ways of handling the same need (May *et al*., 2015), we have chosen to host our resource URIs on a separate domain that we control[2] but which is not tied to our organisation name. From such a URI we use a HTTP 303 response to redirect to the relevant document on a domain that does carry our organisation name.[3] This document could be a typical HTML webpage, a JSON object or a RDF representation (Figure 3). All these different documents offer us a similar, but not necessarily identical, view on an information object. An HTML webpage might show a map that can be navigated by a user. While the JSON representation might provide a GEOJSON representation of a geometry that needs to be visualised in some other way before it becomes useful to a human. Since all the document representations share the same URI, a mechanism is needed to select which representation is requested. This is done through a core HTTP mechanism called content-negotiation. A client requests a URI and includes an Accept header indicating what kind of representation it's looking for. The server analyses this request and sends back the representation that best matches the client's request.

Our URIs are being used everywhere, even on paper. Several of our applications run a process wherein our agency has to communicate with other parties such as archaeologists who have submitted a report or people who have submitted an accidental archaeological find. This could be a letter of acceptance or a letter stating that a certain process was started with some further information of what is expected of the other party. For legal reasons, most of these letters are still mailed out as paper letters. With these types of communication it's common to include an identifier to facilitate further communications. While previously this would have been a random piece of text, we are now using URIs directly in these letters. This makes it much easier to go from an analogue document (the letter) to the corresponding dossier. Previously, one would have had to go to a website or database and enter the random piece of text in a search form. Now it's a simple matter of taking the URI and entering it in a web browser. As long as the user has the necessary security credentials they will receive further information on the dossier.

Our new resource oriented architecture leads to a giant web of resources and looks very similar to the World Wide Web as experienced by humans (Figure 4) or the subject-predicate-object paradigm used in RDF. Every resource is identified by a URI. As noted, all URIs for the information objects are hosted on a different domain than the URIs for the documents about those objects. When viewing the web of resources, it is no longer clear which application is managing a certain piece of information. The client does not need to know where it needs to search for the document. It simply follows the URI and the URI server redirects the client to the correct document. When we decide to move a certain

[2] https://id.erfgoed.net

[3] https://something.onroerenderfgoed.be

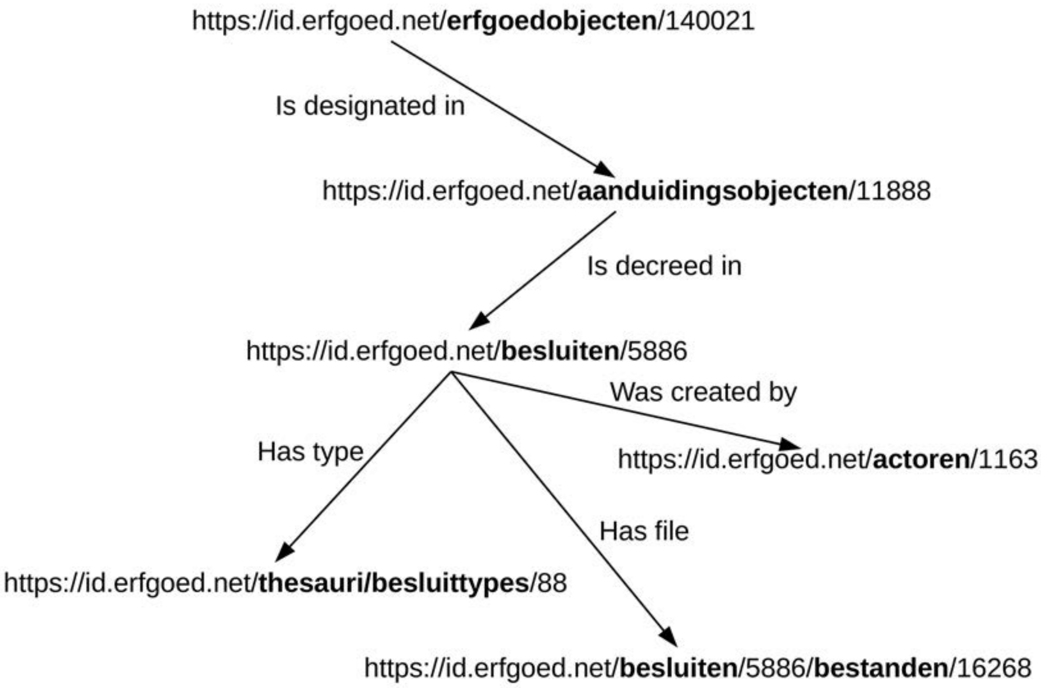

Figure 4. A small part of the web of resources detailing the links between a heritage object, a designation object and a decree.

document to a new application, we also update the mapping from the resource to the document. The client remains blissfully unaware. It just keeps on requesting the resource URI and gets a redirect to a new document URI. From a technical point of view this provides the application developers with a tremendous amount of flexibility. As long as we honour the agreed upon contracts, our architecture keeps on functioning.

Maintaining referential integrity

Every change offers new opportunities, but also creates new issues to be solved. While we have gained a lot of flexibility, we have also lost some convenient solutions to common problems. When all data is hosted in a single database, it's fairly simple to maintain referential integrity. By this we mean ensuring that all links between objects remain valid. If we assign 'person X' as the author of 'document Y' and a user tries to delete 'person X', we want to stop them (or at least warn them). A typical RDBMS like PostgreSQL is well equipped to handle this. But, when you spread out documents over several different systems, things become more complicated. Not every system uses the same database, some systems might use a different database technology (e.g. a NoSQL database) and some might not use a database at all. To alleviate this problem, we have moved the responsibility of handling referential integrity from the database layer to the application layer. Whenever a client asks a server to delete a certain resource, the server contacts a central registry. This registry receives a few parameters from the client and consults a set of servers to determine if a particular URI is in use somewhere. Every server responds with a clear yes or no answer and some additional information, such as how often the URI is being referenced, and a small list of its own resources that reference this particular URI. The central registry aggregates all responses of the different servers and communicates these back to the client who can then determine if the original request to delete a certain resource should be honoured or not. To help our editors, the same service can also be queried proactively. This allows them to check if a certain resource is still in use before actually trying to delete it. To implement this registry, a common JSON exchange format was created, as well as an open source implementation of the registry in Python (Flanders Heritage Agency, 2015). We'd like to emphasise that the exchange format is open to be used from several different platforms. It is currently being used to communicate between our newer Python applications and our older inventory management system written in PHP. Adding newer platforms is a simple matter of implementing a few services.

Publishing Linked Data

As mentioned before, government agencies are encouraged and even required to publish as much of their data as possible under an open data license. We follow the Flemish Open Data guidelines by publishing under the Flemish Free Open Data License. To make it

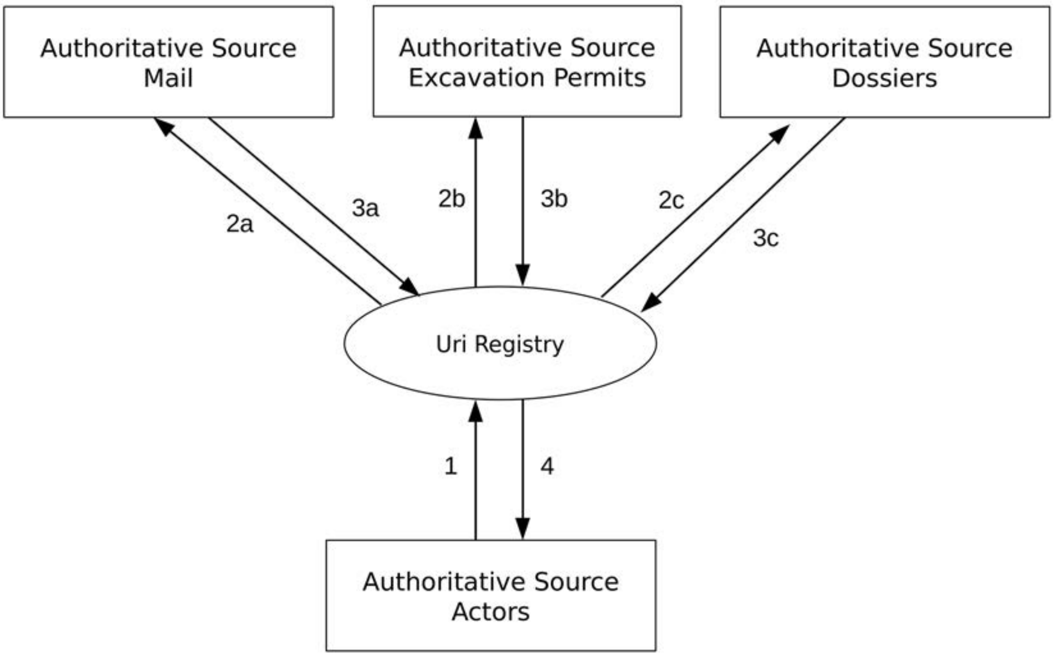

Figure 5. Evaluating referential integrity through the URI Registry. 1. Client asks the registry where a certain URI is being used. 2. Registry consults authoritative sources. 3. Authoritative sources reply. 4. Registry collects responses and replies to the client.

easier on external providers who do not operate within Flanders, we also publish as CC-BY 4.0.

From a resource oriented architecture it is a surprisingly small step towards publishing linked data (Berners-Lee, 2009) and RDF. In effect our architecture is built around the concepts of linked data in the broadest sense, by linking resources that can be dereferenced through URIs. Our standard HTML webpages and JSON services already adhere to this. If we look at linked data in a somewhat stricter sense, there is one key aspect missing. A JSON document for a heritage object might refer to the URI for a church in our thesaurus in its type field, but the type field itself has no URI that can be dereferenced.

All that remains to be done to publish our data as RDF data, is therefore to map fields in our service to predicates. We have started doing this for newer systems. Where possible we have reused existing vocabularies such as Dublin Core, FOAF, SKOS, etc. Most of our predicates come from these vocabularies, but where necessary we have created new ones (Van Daele, 2016). We have also created new classes for each of our resource types, mainly so we can use them in rdfs:domain and rdfs:range statements. In later iterations we plan to map our classes to existing classes in other ontologies. When publishing a certain resource as RDF, it is now very simple to publish this resource as a graph of triples. The resource becomes the subject of the triples. The attributes of the resource become predicates. And the values of those attributes either become literals when dealing with intra-resource information, or they become URIs to other resources when dealing with inter-resource information. These transformations are done within the application itself making them easy to maintain and very lightweight to publish. The RDF data does not live in a separate system requiring a separate Extract-Transform-Load (ETL) step. Because of this, our data is always guaranteed to be up to date.

Our services typically consist of two different types of documents. The most prevalent group contains documents about individual resources. Each of these documents represents a single resource with its attributes and relations to other resources. The document itself lives at a document URI,[4] that is the document about a certain resource, identified by a resource URI.[5] Our document can be retrieved in different serialisations through content-negotiation (Figure 6). The first serialisation, HTML, presents a web page that is meant to be read by the people interacting with a system. It tries to be as attractive as possible with little technical jargon. The other serialisations, JSON, RDF/XML and RDF/Turtle, are meant for machines.

Apart from these documents about a single resource, we also offer documents about a collection of resources.

[4] e.g. https://besluiten.onroerenderfgoed.be/besluiten/5825
[5] e.g. https://besluiten.erfgoed.net/besluiten/5825

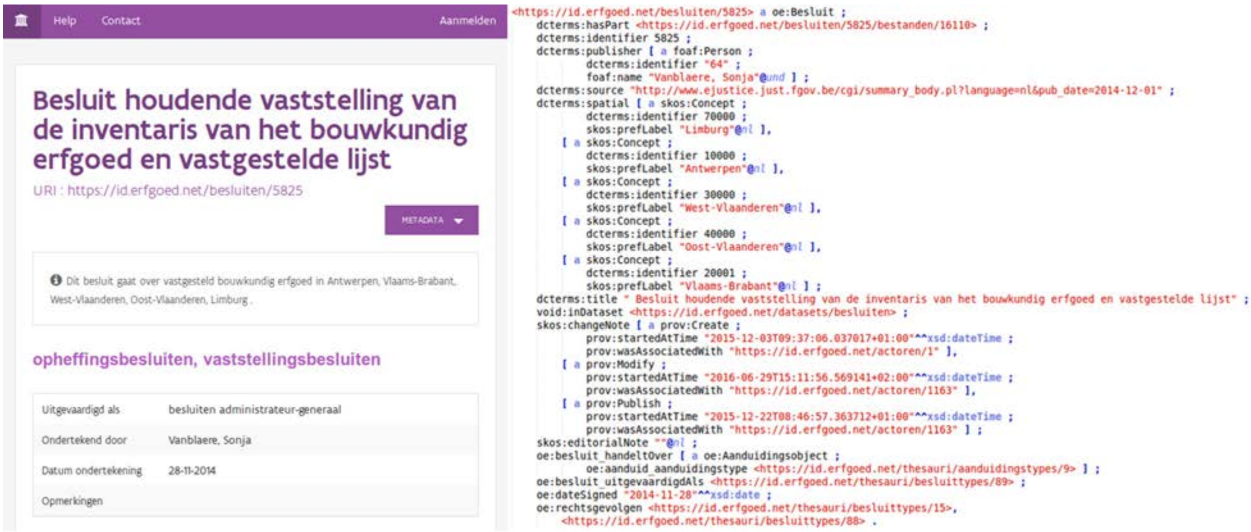

Figure 6. Different serialisations of one resource. On the left an HTML web page meant to be seen by a human user. On the right a Turtle document meant to be read by a machine.

These have a document URI, but not a resource URI. They are typically used in querying and searching. A URI such as https://besluiten.onroerenderfgoed.be/besluiten?beschermingstypes=https://id.erfgoed.net/thesauri/aanduidingstypes/1&sort=id produces the collection of resources that are decrees that have created listings of monuments, sorted by id. Again this document URI supports content-negotiation. In general, paged serialisations as HTML and JSON will be available. In certain cases, we also offer a serialisation as csv. The HTML version contains a typical search interface for human end users. The csv interface is meant to be downloaded by machines or humans for further processing. The JSON version is solely aimed at machines. At the moment, a collection like this cannot be serialised in an RDF format. We are considering implementing this by adopting the Hydra Core Vocabulary (Lanthaler and Gütl, 2013) when it reaches a stable enough state.

In a later stage we might add a triplestore and a SPARQL service to our architecture. At this moment we are still analysing how to implement this and whether this is actually a valuable addition to our setup. While we recognise that this provides some powerful querying features, this would also require setting up a separate infrastructure and creating a new ETL procedure that might become a burden to maintain. A fully functional SPARQL endpoint offers a lot of flexibility, but can also put a serious strain on resources. See Verborgh *et al.* (2016) for a full discussion on this topic. As an alternative we are following the work done on Linked Data Fragments and the Triple Pattern Fragments interface (Verborgh *et al.*, 2016) that offers an intermediary approach.

Spatial Data Infrastructure

Within Flanders Heritage we generally make very little distinction between spatial and non-spatial data. Whenever we build JSON serialisations of our data, we include our spatial data as GeoJSON. However, we have always realised the potential in GIS system for integrating very heterogeneous data sets. As indicated by the term immovable cultural heritage, our data sets have a very strong spatial component. Thus, a well-equipped Spatial Data Infrastructure (SDI) is needed. Just as in other countries (McKeague *et al.*, 2012), most of our data sets have been published under the Annex I Protected Sites theme according to the INSPIRE directive. We publish Open Geospatial Consortium (OGC) services on our own SDI node that gets harvested by INSPIRE through the intermediary Mercator and Geopunt SDI nodes.

It has been noted before that there is no good application schema for cultural heritage within INSPIRE (Uriarte González *et al.*, 2013). We have worked around this limitation by using our network of linked data, adding the URI attribute of the corresponding resource to the features returned by our geographic services. This enables a client to easily request further data on a certain object. While we still publish other attribute data through our geographic services, we see these as a mere convenience. Within our geoportal,[6] we integrate our own WMS layers with other INSPIRE services (Figure 7). This geoportal is custom built to provide a tight focus on cultural heritage and uses our URIs where possible. Whenever a user clicks on the map they get a report of all features at this location. By

[6] https://geo.onroerenderfgoed.be

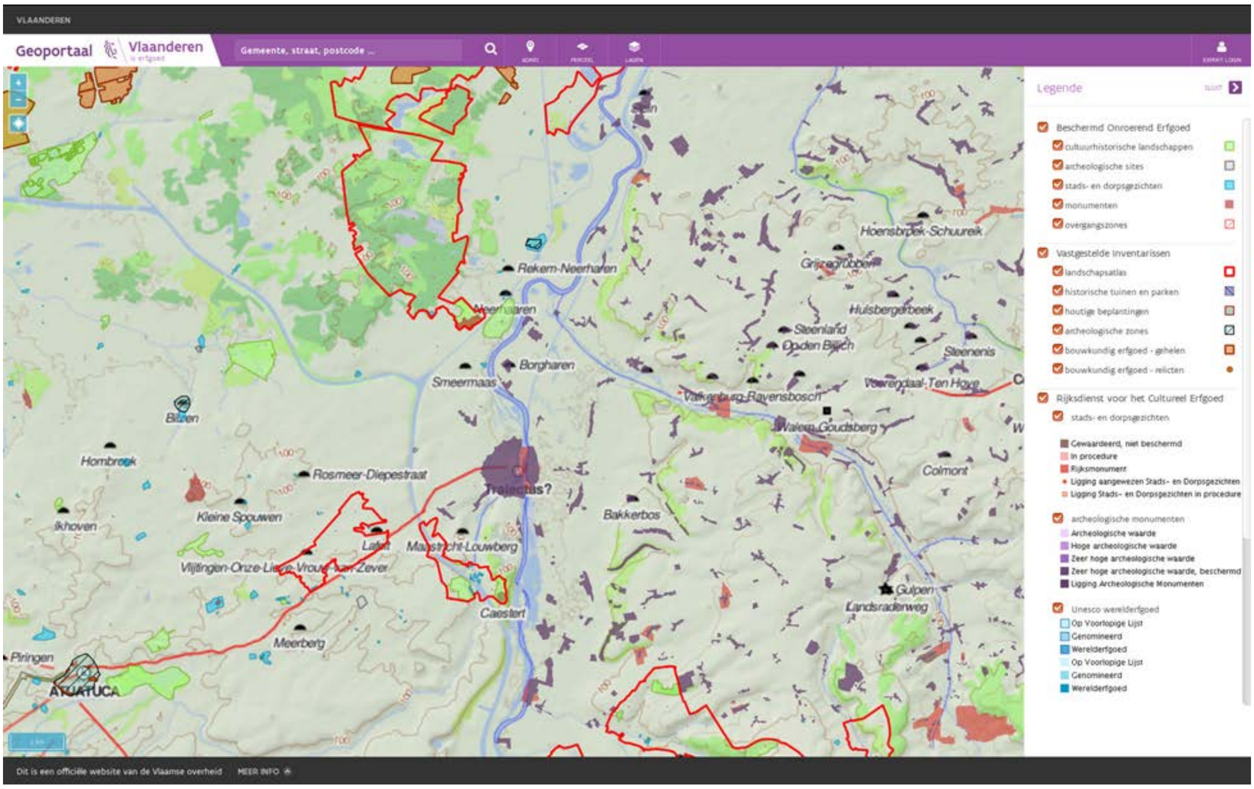

Figure 7. The geoportal combines internal and external layers. This example shows a map of the Roman Empire provided by Pelagios, combined with FHA layers (on the left) and RCE layers (on the right).

following the URI attributes of these features, links to web pages containing more information are presented to the user.

Outside of the standard suite of OGC services, we have also created a custom geosearch service. This is a very simple service that allows a client to query all heritage within a certain perimeter (a geometry), possibly enhanced with a buffer and filter by a limited list of parameters. This custom service was built because it allowed taking control of the generated output, tailoring this to our needs. It also made it possible to make some performance optimisations. Currently, only JSON output is supported. As always, an integral part of the output is URIs that point toward the full information objects that were found. While the service was created to support our Zoning component, it is also being made available to the wider public and can be used by external parties to query our data.

Joining the ocean

While we have created our own archipelago, we are still somewhat removed from the huge ocean of data out there. So far we have found surprisingly few linked data sets we could link to. Our explorations of the Flemish[7] and Belgian[8] open data portals have turned up lots of aggregated data sets (e.g. The population divided by sex and age at a certain point in time) that quite often have little to do with cultural heritage and are unsuitable for linking because of their aggregated nature. The most promising data sets to link to are geodata-sets such as CRAB (address data). But while these do contain stable identifiers for geographic objects, these have not been turned into URIs at this point of writing. Similarly, there exists a data set of administrative subdivisions of Belgium (regions, provinces, communities) that contains identifiers but not URIs. We do sometimes link to other external webpages from within our heritage inventories, but these links generally only point to HTML webpages that do not necessarily have a very stable URI and there is no structured data available at this URI.

On an international level we have found a few more prospects with the cultural heritage community. So far we have been creating links between our own controlled vocabularies and thesauri and international thesauri. This is fairly easy to do on both a technical and a conceptual level. We currently link to the Art and Architecture Thesaurus provided by the Getty Research Institute and the heritagedata.org thesauri (May *et al*.,

[7] https://opendata.vlaanderen.be

[8] http://data.gov.be

2015). A further step might be to connect our thesaurus of periods to the PeriodO gazetteer (Golden and Shaw, 2016).

On a purely cartographic level there does exist a wealth of information within Belgium. As noted before, we do make regular use of GIS open data sets of other government agencies in Flanders that are available. While these allow us to display our data on different basemaps in our geoportal, it does not provide for a truly integrated and linked data experience. On an international level we have incorporated both the Pelagios Imperium Romanum basemap (Åhlfeldt, 2012) and some cultural heritage map layers by the Cultural Heritage Agency of the Netherlands in our geoportal (Figure 6). While this does visualize data across borders it provides for little actual integration. It has, however, been an interesting first step that required little effort. The fairly simple integration of WMS and TMS services seems to be much easier to achieve than the more powerful but much more complicated integration of linked datasets.

Conclusion

Often linked data is seen as a good way to publish data and link it to other data. While this is certainly the case, we have found that it can be much more. By adopting the basic principle of linked data, naming things with HTTP URIs and linking them with other HTTP URIs, we have made linked data as the representation of our information resources the cornerstone of our enterprise architecture. It has proven to be as efficient for creating and maintaining data as for publishing it. Flanders Heritage will keep on adding islands to its little archipelago. Hopefully we'll also be able to find some new shipping lanes to other seas.

Acknowledgements

We wish to express our gratitude towards Philip Carlisle (Historic England) for proofreading this work and helping us find matching labels for often similar but not exactly the same concepts. We would also like to thank all colleagues at the Flanders Heritage Agency, both the IT colleagues who help shape and expand the system architecture and those heritage professionals who interact with it on a daily basis.

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GIS and Spatial Analysis

Mieko Matsumoto and Espen Uleberg (eds) 2018. *CAA2016: Oceans of Data*
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
Oxford: Archaeopress

Crossroads: LCP — Model Testing and Historical Paths During the Iron Age in the North–East Iberian Peninsula (4th to 1st Centuries BC)

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Abstract
The objective of this paper is studying overland travels during the Iron Age (4th to 1st centuries) in two areas of the northeast of the Iberian Peninsula. There is a broad consensus on river transport, but the roads used by the Iberians are mostly unknown because there is a lack of studies about terrestrial travels and path persistence during this era. It is assumed that overland travels, the ones that were related to everyday activities and the distribution of goods and freights to the Iberian settlements, were carried out on foot, by carts, and pack animals. Taking into account that the Least-Cost Paths (LCP) calculations may be useful in order to understand the logic behind the historical paths, we use and compare the most well-known GIS LCP routines in order to approach the Iberian terrestrial transport network and its persistence over time and landscape by simulating different scenarios.

Keywords: Iberian Peninsula, Iron Age, Least-Cost Paths, terrestrial transport routes, path model testing, path persistence

Introduction

Scholars have paid little attention to local and medium-range communications in ancient Iberia during the Iron Age. It is assumed that overland travels were performed on foot or by the use of carts or pack animals when the moving of freights was required. Horses, donkeys and oxen were the most suitable animals for this purpose.

Research on Least-Cost Paths (LCP) has been in development for many years (Bell and Lock, 2000; Bell *et al*., 2002; Bellavia, 2006; Ejstrud, 2005; Fiz Fernández, 2008; Fiz and Orengo, 2008; Gietl*et al*., 2008; Gorenflo and Gale, 1990; Groenhuijzen and Verhagen, 2015; Herzog, 2010; Herzog and Posluschny, 2008; Howey, 2007; Llobera and Sluckin, 2007; Murrieta-Flores, 2010; Zakšek*et al*., 2008). In view of lack of studies on our area and in protohistoric chronology, we decided to compare the application of two LCP routines, in order to answer the following research questions:

- Are LCP routines useful for detecting hypothetical Iron Age roads?
- Which factors are involved in the structuring of the road network (use, topography, natural passes, settlement pattern, time saving or energy saving)?
- Are there roads persistent from the Iron Age?

We cannot forget that there are some factors that we cannot model, such as the symbolic or cultural dimensions of movement. Our study will be structured on two levels: on the one hand, short distance travel, those that take place within a radius of around 30km or less and seen as equivalent to a one day trip (Zamora Merchán, 2006). In this sense it is of prime importance to understand the recurring journeys in the surroundings of the sites, as they were part of the Iberian people's everyday life. This local environment corresponds to Hobsbawm's 'little world' (Hobsbawm, 1973) which Grau recalls (Grau Mira, 2011) as the frame work in which everyday activities took place. These included farming, community celebrations or journeys to market places. On the other hand, consequently we will consider long distance travel, those exceeding the 30km one day trip.

Geographical and cultural context

The Iberian culture flourished in the eastern area of the Iberian Peninsula and the south of present-day France during the Late Iron Age, i.e. between the 6th and the 1st centuries BC. The Iberians were a mosaic of tribes that, despite their cultural homogeneity, never acted as a political union. The zenith of the Iberian culture is documented between the 4th and the 3rdcenturies BC. In this paper we will focus on two areas of the north–eastern Iberian Peninsula: Cessetania and the western Ilergetian territory.

Cessetania is a relatively small area with a typical Mediterranean orography in the present-day province of Tarragona (Catalonia). It is bordered on its north–

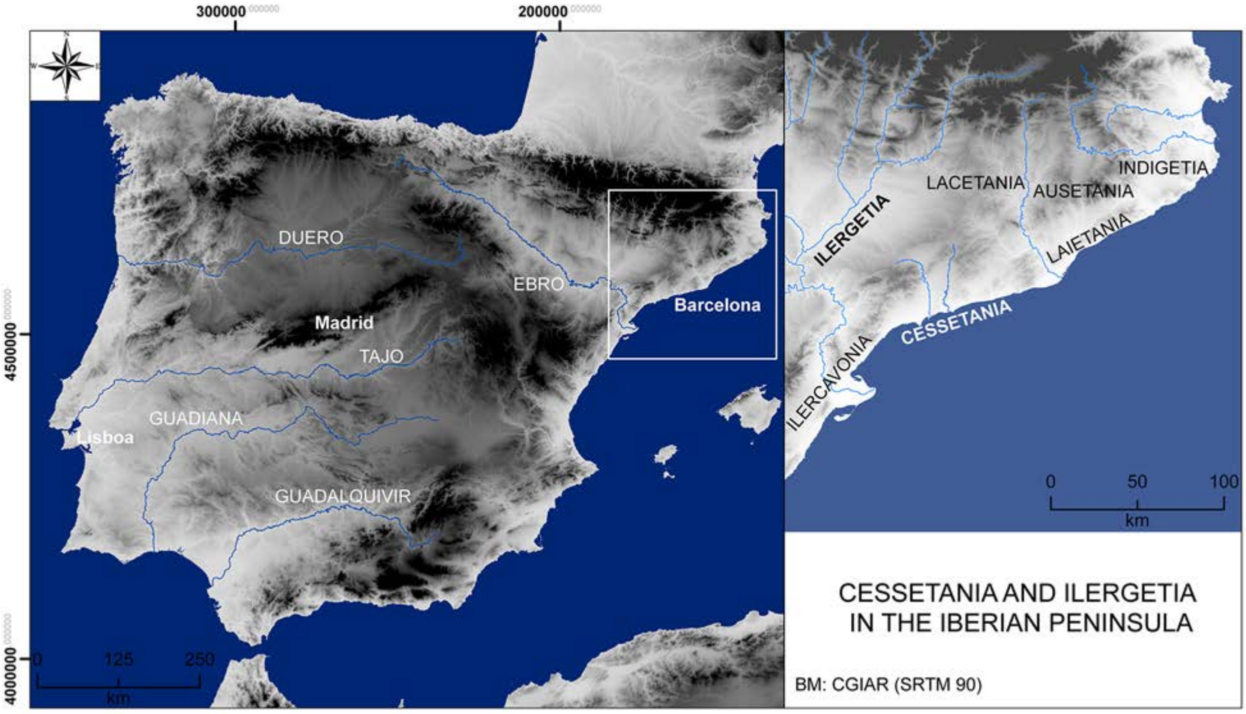

Figure 1. The Cessetània and the Western Ilergetia in their geographical context: the Northeastern Iberian Peninsula.

western side by the Prades Mountains and to the east by the Garraf Mountains. In front of the mountains, extensive plains descend to the Mediterranean Sea. The main water courses in the area are the Francolí and the Gaià, two low-volume rivers that flow from north to south to the coastal towns of Tarragona and Tamarit respectively.

The Ilergetian territory comprises a vast plain located between the coastal mountain range and the Pyrenees. Today it is divided between western Catalonia and the east of Aragón. During the Iron Age, however, the whole region was part of the Iberian cultural continuum. This plains area is traversed by two main rivers, the Cinca and the Segre, which cross this hinterland from north to south, eventually flowing into the Ebro. Except for these two major arteries, the landscape is characterised by great rain-fed plains crossed only by seasonal streams and where major grain farming flourished. This is demonstrated by the archaeological records, which show a high population density especially between the 4th and the 1st centuries BC (Sanmartí, 2004) (Figure 1).

Horses, oxen, donkeys and mules: pack animals in Iberian settlements during the Iron Age

Horses, oxen, donkeys and mules were the most common pack animals during the Iron Age. There is plentiful evidence of their presence in Iberian settlements. Horses were very common, although they were mainly linked to the warrior elites. Therefore, this animal had also a symbolic dimension and was the object of ritual practices. We have to mention the case of the Iberian fortress of Els Vilars (Arbeca, Catalonia) where 15 miscarried horse foetuses were deposited as foundational offerings below several houses from the Early Iron Age to the Iberian period (Figure 2). The presence of rider and horse-related warfare equipment in Ilergetian cremation burials (Graells i Fabregat, 2008; Ripoll, 1959) shows that owning a horse was of prime importance for the Ilergetian aristocracy. During the 2nd Punic War, their appreciation among the Iberian elites was well known to Scipio who, in 208 BC, following the Battle of Baecula, presented the Ilergetian *regulus*, Indibil, with 300 of his finest horses (Pol. 10, 40; Liv. 27, 19).

In summary, horses were luxury possessions; they were not essential for subsistence activities, but were used for military and ostentation purposes (Nieto, 2012, p. 689). Slicher van Bath (1974) points out that horses were not used as draught animals until 1000 AD; before that, they only appear in aristocratic burials and other ritual contexts. Bovines are the most versatile animals for human use; they provide milk, meat, leather and especially working power. Bovines, especially bulls and oxen, as we have seen in the case of horses, had a symbolic dimension in most Mediterranean Iron Age Cultures. They often appear in ritual scenarios such as burials, offerings or commensality rituals and they also form part of foundation rituals.

Oxen are the castrated male individuals of the bovine species and because of that they are docile and suitable for domestication. Like horses, oxen have very demanding food requirements. Moderato Columela (Col. 6, 3) describes the optimal feeding for stabled oxen: if they are not in an intensive regime, they need at least 8 to 9 hours of pasturing per day, depending on the availability of fresh pastures and the seasonal changes. The use of this kind of animal for pulling carts or ploughs is described in Roman agricultural treatises. This is confirmed by the skeletal remains found in Iron Age archaeological contexts in the north–eastern Iberian Peninsula, which frequently show pulling-related pathologies (Colominas Barberà, 2009, pp. 39–40).

Last but not least, it is necessary to talk about mules and donkeys (Figure 2). They are extremely versatile and tough animals and can be used for riding or as pack and draught animals. They also have the ability to adapt to harsh terrains and are generally docile and easy to train, meaning anyone can drive or ride them, even a child.

Selective breeding has focused on maximising these features, as well as on obtaining bigger, stronger animals. The size and weight of an average *Equus africanus asinus* has increased over the centuries. The weight of a modern donkey ranges from 130 to 240 kg and its height varies from 1.40 to 1.60 m at the withers. Although it is well known that donkeys first came to the Iberian Peninsula with Phoenician traders, identifying their skeletal remains at Iberian sites is difficult due to their resemblance to horses. However, there is archaeological evidence showing that prehistoric donkeys and mules were much smaller than their current counterparts. The size of an Iron Age specimen from the Iberian Peninsula, in particular from the neighbouring region of Valencia, ranges from around 0.89 m to 1.20 m tall at the withers (Colominas Barberà, 2009, p. 55). In summary, protohistoric donkeys and mules were smaller than current ones, although this did not prevent their use as draught animals. This point is confirmed by presence of draught-related pathologies on protohistoric donkey skeletal remains (Colominas Barberà, 2009).

Figure 2. Askos, 3rd Century BC; donkey carrying wine amphorae (MARTA, Taranto, Italy).

With regard to maintenance issues, feeding a donkey is cheaper than feeding an ox or a horse. In this respect, we would like to point out that a donkey requires 25% less food than a horse of the same weight. The amount of food required in order to sustain a donkey ranges from 1.5 kg per 100 kg of weight for a resting animal to 2.3 kg per 100 kg for a working specimen, not to mention the fact that a large part of their diet is based on dry matter, a consumption that is higher in donkeys than in other large herbivores (Chirgwin *et al.*, 2000). Last but not least, we have to mention their longevity, which ranges from 15 to a maximum of 30 years, depending on how much they work and how well they are cared for. The skeletal remains indicate a late slaughtering age, when their strength decays (Colominas Barberà, 2009).

Mules and donkeys are much stronger than bovine cattle (Johnstone, 2004; Colominas Barberà, 2009, p. 134). A single donkey can carry a load of between 27% and 40% of its own weight on its back (Hanekom, 2004, p. 192) and walk around 20 to 30 km in a six-hour working day. The possible load increases using a cart: a donkey pulling a 100 kg cart is able to move a load of 400 to 500kg over flat terrain; in this case, the speed decreases to 2–4 km/h (Chirgwin *et al.*, 2000), meaning that it is able to travel around 12–24 km a day, depending on the size, the weight of the animal and the load. However, the gradient will affect performance; if the gradient increases to 5%, the load the animal is able to move decreases to 150–200 kg (Hanekom, 2004, p. 193).

In view of the aforementioned, we believe that mules and donkeys were the most suitable animals for goods traffic in areas such as Cessetania and the Ilergetian hinterlands. In order to corroborate this statement, and taking into account what we have already described, we tested three premises:

1. A single walker of 80 kg

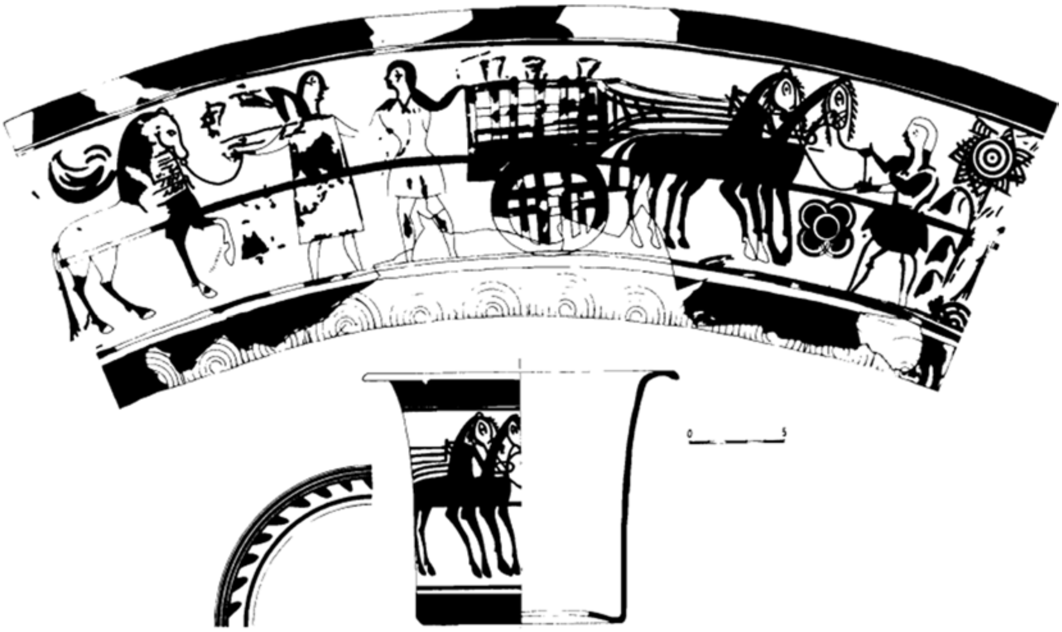

Figure 3. Kalathos of Elche de la Sierra (Albacete, Spain) depicting a cart pulled by two donkeys; late 2nd Century BC (Source: Eiroa 1986).

2. A 180 kg donkey with a 50 kg load on its back at a speed of 5 km/h
3. Two 180 kg donkeys with a 100 kg cart of carrying 300 kg load at a speed of 4 km/h (Figure 3)

Methodology

Creating a clean DEM and topographic restitution

The first step needed in order to perform the aforementioned experiments is creating Digital Elevation models of the two areas. We have obtained them using the LIDAR data available from the Instituto Geográfico Nacional and the Institut Cartogràfic i Geològic de Catalunya.

Being aware of the need of topographic restitution in order to avoid present-day structures to alter the results of our calculations, we cleaned the points related to modern features to obtain a bare earth DEMs on ArcGIS 10.3 (Figure 4). We have obtained 5 m/cell DEMs for large scale tests and 2 m/cell for testing on local areas.

LCP Calculation routines

The aim of this experiment was to offer a first approach to the question of mobility during the Iron Age in two areas of the north–eastern Iberian Peninsula by comparing the LCPs obtained with different methods.

As in Ejstrud (2005), we have used two formulas:

- First of all we applied the Hiker's formula (Tobler, 1993), where:

$$v = 6e^{-3.5[s+0.05]}$$

V stands for speed and S for slope in degrees. This formula allows us to simulate the movement pattern for a single walker, informing at which speed a hypothetic hiker would cross each cell of the Digital Elevation Model, taking the gradient as a main variable. The results of this calculation are expressed in km/h per cell. This is quite a simple calculation, but clearly shows the cost of moving through a digital landscape taking the time into account.

Secondly, we used the formula proposed by Pandolf (Pandolf *et al.*, 1977) to calculate the cost in energetic terms of crossing a certain terrain. It is much more accurate than the first one, since it takes into account more variables. The result of this equation (m) expresses the metabolic ratio in watts per cell.

$$m = 1.5w + 2.0(w+l)(l/w)2+n(w+l)(1.5v^2 + 0.35v*abs(g+6))$$

It takes into account the following variables:

(w) refers to the bodyweight of the person or pack animal, (l) to the weight of a hypothetical load, (v)= refers to the speed, and (n) to the terrain factor — in our case a raster layer which simulates the effort of crossing rivers and streams —; and finally (g) for the gradient. In summary, it measures the metabolic cost of moving through the DEM.

We find that Hiker's formula is suitable for simulating human movement taking the slope as the main variable. Using Pandolf's formula allows us to experiment and simulate the movement not only of a single walker but also of different kinds of pack animals with different loads. Recently Groenhuijzen and Verhagen have rewritten Pandolf's equation in order to obtain a result expressed in meters/second per cell instead of watts per cell (Groenhuijzen and Verhagen, 2015, p. 30).

Setting start and endpoints for LCP

In the Ilergetian case, the start and endpoints for the LCP long range experiment were set by carrying out a morphometric analysis using Landserf 2.3, with the aim of detecting natural points of entrance, in order to identify the main communications corridors (Figure 5). We also took into consideration some well-known fordable places in the fluvial network. This method is based on P. Murrieta's experiments with Least-Cost Paths in the western Sierra Morena Mountains (Murrieta-Flores, 2012). In the Cessetanian case, the start points are major Iberian sites. It is assumed they played a role in the organisation of the area and we wished to investigate this assumption by comparing the LCP road network generated by both methods.

For the short range experiments, we used Iberian sites as start and endpoints (Figure 7), selecting different kinds of settlement. First of all, we distinguished urban sites that may have acted as marketplaces and craft centres; secondly, we used small villages which have an intermediate function, possibly acting as stops along commercial routes. Finally, we took into account small farms from where peasants had to travel to the main and intermediate marketplaces in order to buy and sell their goods and wares.

Lastly, with the aim of understanding the role of the LCP in the origin of the road network, we identified the historical roads by mapping mediaeval and modern era documentation and 19th and 20th century cartography, such as the first edition of the *Mapa del Territorio Nacional* for both areas (Figure 8).

The identification of natural corridors has been proposed on the method based in Murrieta's experiments in western Sierra Morena, which consisted in using the line density tool in ArcGIS 10.3 in order to identify the parts of the DEM where movement is easy (Murrieta-Flores, 2012). Finally with the aim of quantifying the

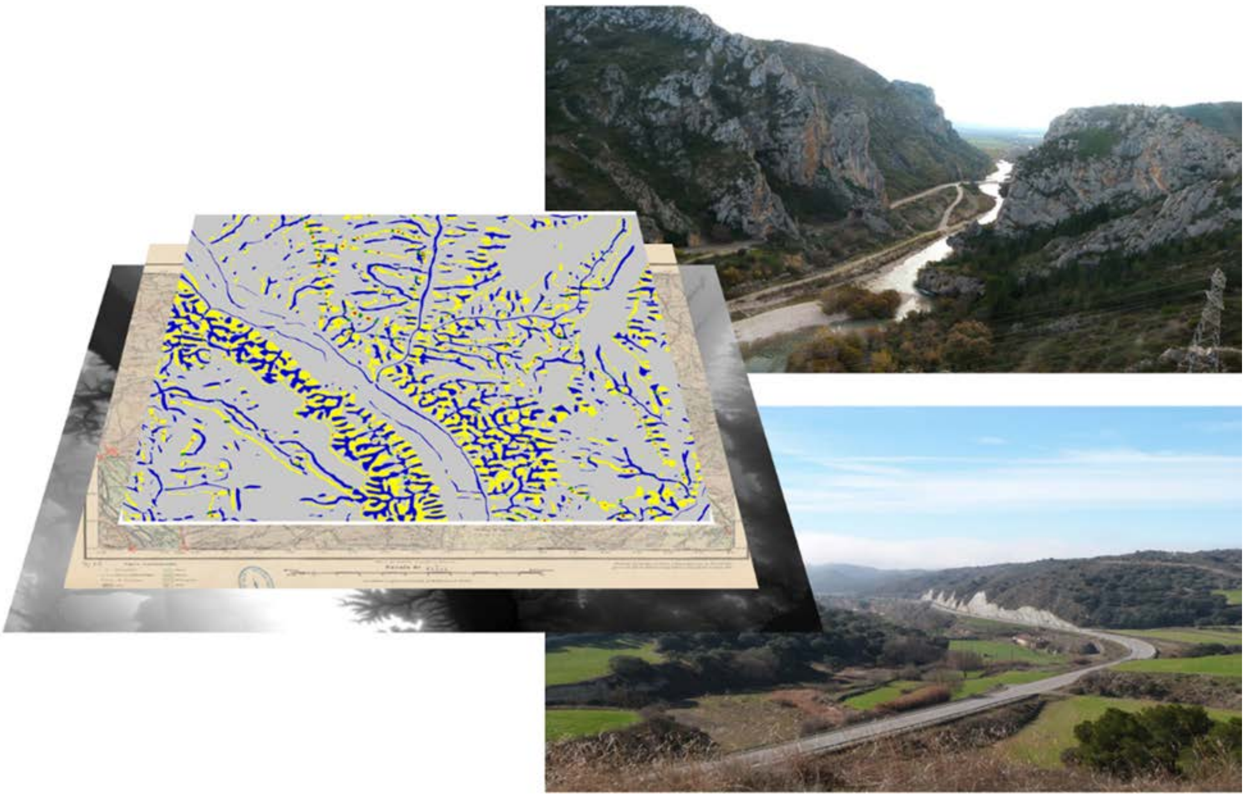

Figure 4. Identifying passes to the Ilergetian territory with Landserf 2.3: the right side views Strait of Santa Ana and the pass of Alcampell, both were used as entrance points in the long range experiments.

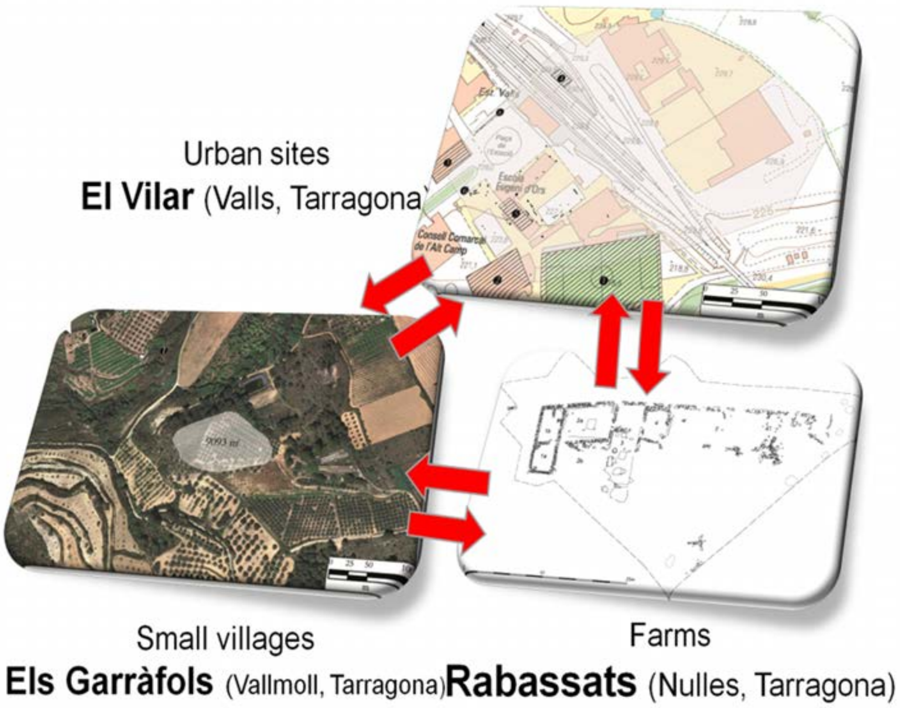

Figure 5. The Cesetanian case: using Iberian settlements as start points and end points.

degree of similarity of the LCP and the historic roads we have mapped the historic road network and created 100 m buffers around the paths,then we have calculated the number of km and the percentage of matches.

Results

As we pointed out above, we calculated the LCP road network using a Hiker's formula and a Pandolf's formula based cost surfaces, selecting different start and endpoints and then compared the results.

In the case of Cessetania, long range experiments (Figure 9) using Pandolf's method revealed major coincidences with historical roads, i.e. around 30% of matches, which corresponds to 25 km of an approximately 80 km-long network. Parts of the routes coincide with the Roman Via Augusta and the ancient Valls to Vallmoll road, which is mentioned in mediaeval documents. The LCPs calculated in the three cases depict exactly the same roads. The LCPs calculated using Hiker's formula has shown fewer coincidences, matching only 12.5 km of the 80 km that correspond to two segments of the Via Augusta.

The Ilergetian long-range LCP experiment consisted in using natural passes as start and arrival points, as in Murrieta's experiments (Murrieta-Flores, 2012). The LCPs created with Pandolf's equation display much longer routes; they try to avoid topographic features, seeking areas with lower gradients and a high recurrence index among routes with a different starting point. They also tend to follow river valleys, which had risk of periodic flooding, but are the lowest areas of the DEM. As in the first case, the LCP network has a 32% coincidence with historic roads.

Broadly speaking, the results obtained with the Hiker's formula in the case of Ilergetia show a quite different dynamic to the one we have just explained. We have been able to generate an extensive road network of around 1000 km, with a 58% match to historic roads (Figure 10). In this respect, we have to mention a clear coincidence with the N.1 route of the Antonine Itinerary, between the Roman towns of Ilerda and Osca, in both long- and short-range experiments. We can hypothesise that this path indicates the presence of a natural corridor, which would have been in use many centuries before the arrival of the Romans, i.e. since the Iron Age. There are also many coincidences with mediaeval roads and cattle roads.

The short-range experiments show similar results, as well as many coincidences with historical roads. In the case of Cessetania,the start and arrival points chosen were the sites of El Vilar de Valls (an urban settlement), ElsGarràfols (an intermediate site) and Rabassats (a farm). In this case, we also calculated the optimal paths for the three cases mentioned in the methodology section (Figure 11).

The Pandolf LCP network has a total length of 19 km, of which 6.7 km or 35.2% coincide with the historic roads. Some of the roads that match are the old Valls

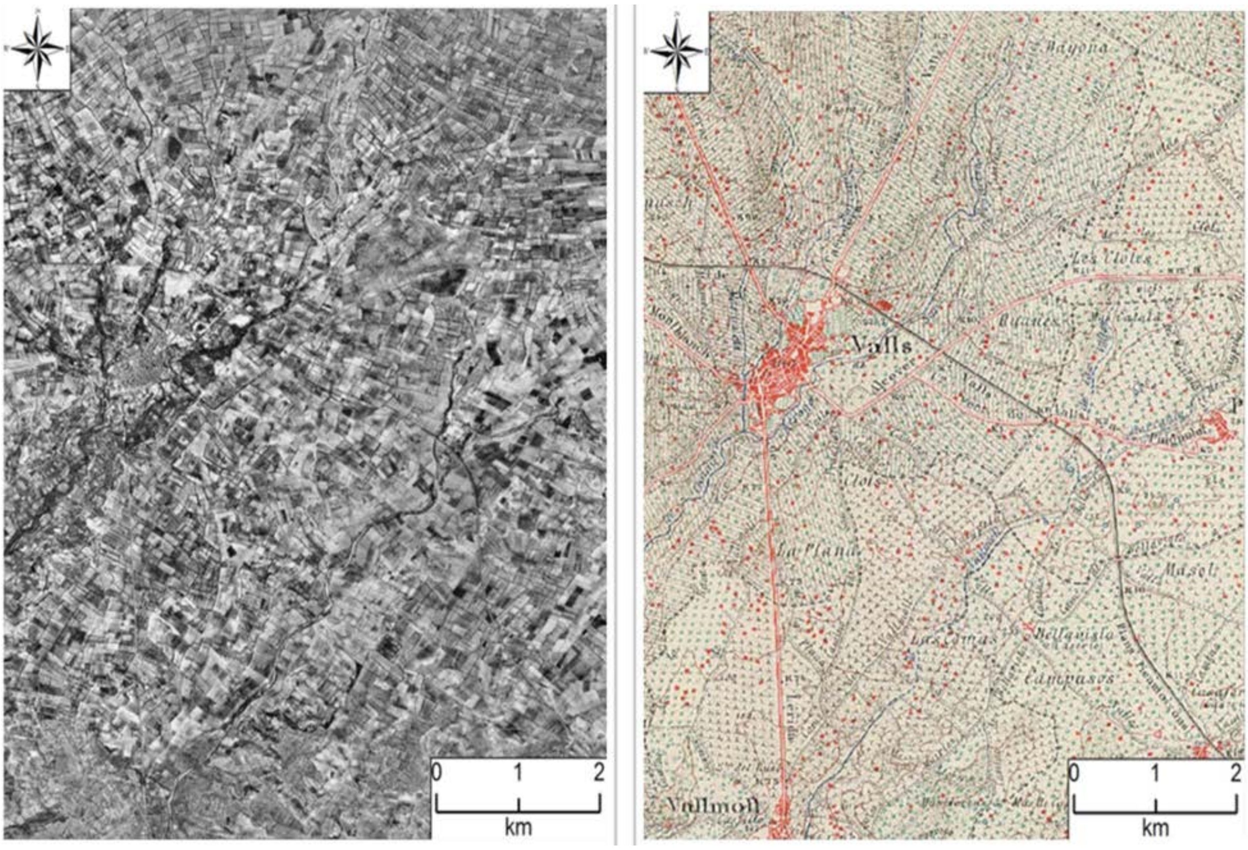

Figure 6. Using the 1956–1957 US Army flight and the first Spanish territory cartographic series in order to identify historic roads.

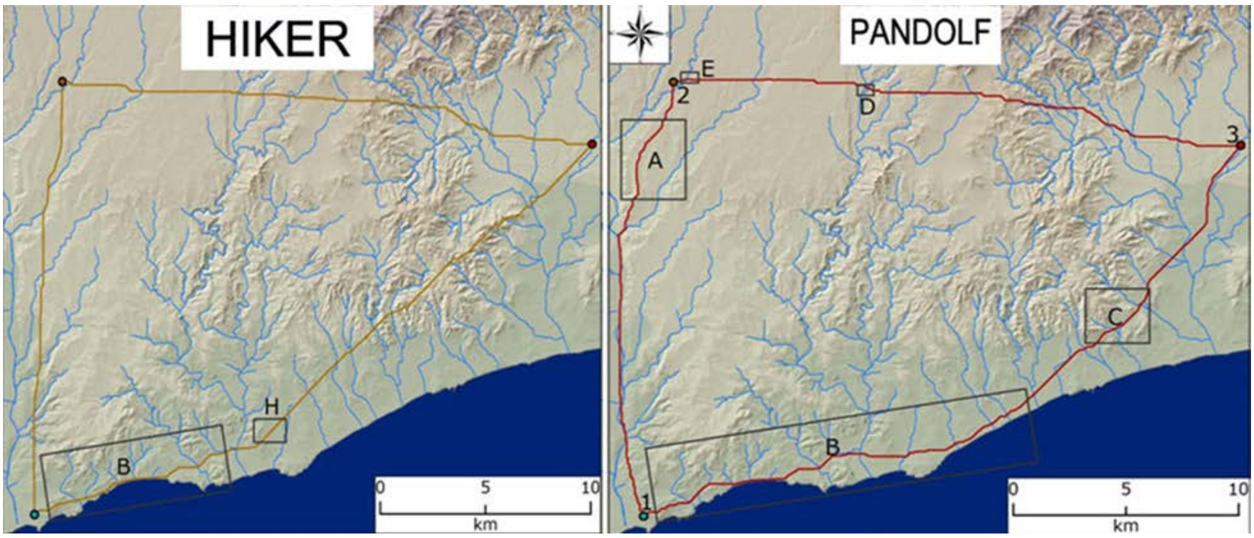

Figure 7. Result of the LCP long range experiments in the Cessetània.

to Vallmoll road, the old Valls to Vilavella road and finally the old Nulles to Vallmoll road. The Hiker's method shows a 16.7 km-long network, of which 7.3 km match historic roads, i.e. 43.7%. In this case the Hiker's formula reveals a certain time saving logic behind the short-term communications.

Finally, the Ilergetian short-range experiments showed major differences between the Pandolf's and Tobler's LCPs. While the Tobler's paths are straight and prioritise time saving, the Pandolf ones are much longer and follow the lowest contours, and the energetic expense calculations display the same result for all

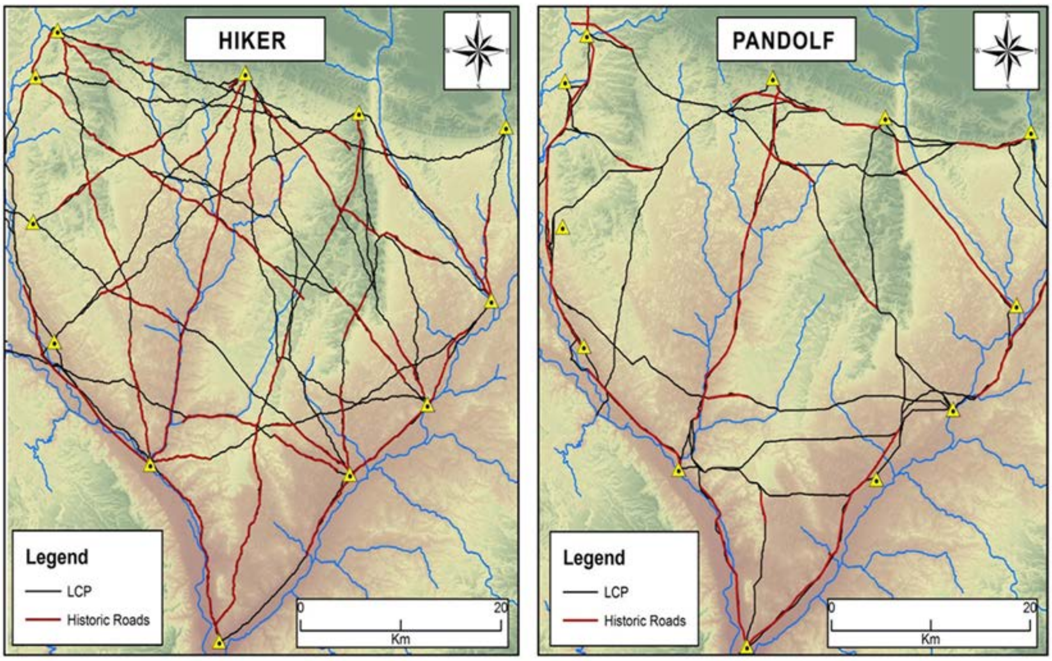

Figure 8. Result of the LCP long range experiments in the western Ilergetian territory.

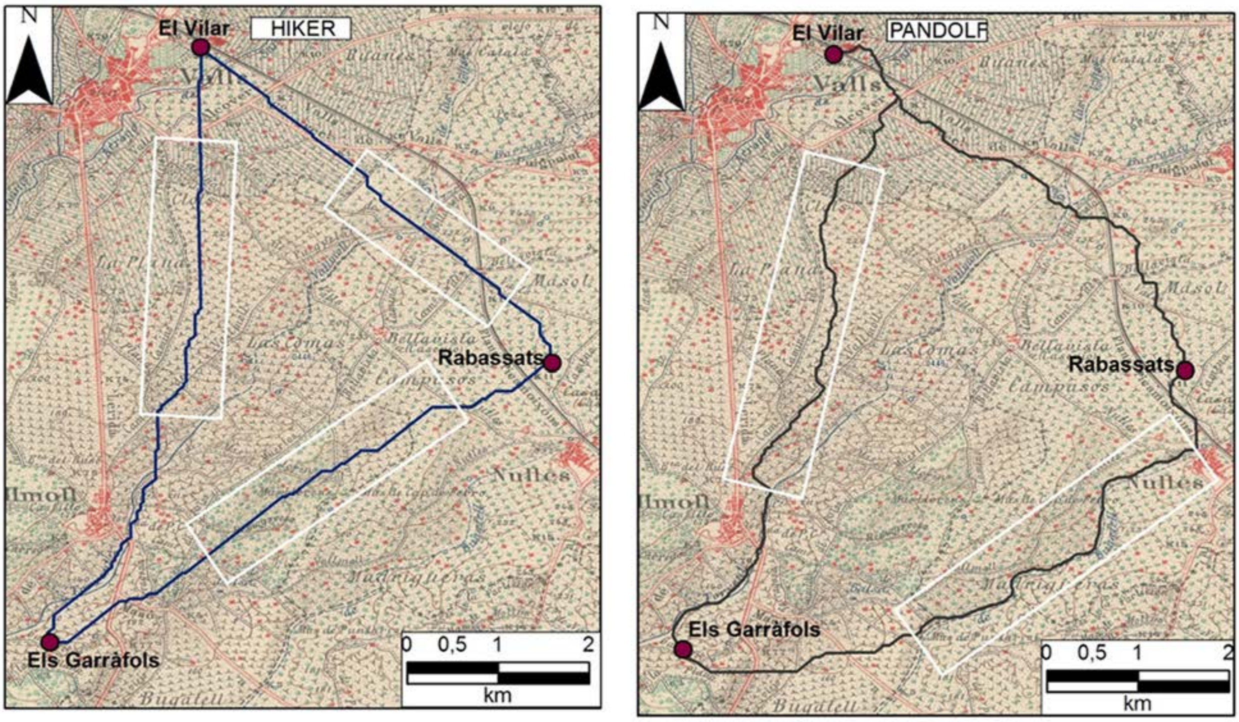

Figure 9. Result of the LCP Short range experiments among El Vilar (Valls), Rabassats (Nulles) and Els Garràfols (Vallmoll), all of them Iberian settlements of the Cessetanian area.

the experiments. The LCP network generated with the Pandolf method is 100.68 km long and only 14.5 km match historic roads (14.40%). The Hiker's network is 85.4 km long and only 15.79 km (18.48%) match the N.1 route of the Antonine Itinerary (Figure 12).

Conclusion

First of all it is necessary to point out that the influence of high-resolution DEMs on the results. We used a 5 m/cell DEM for the long-range experiments and a 2 m/

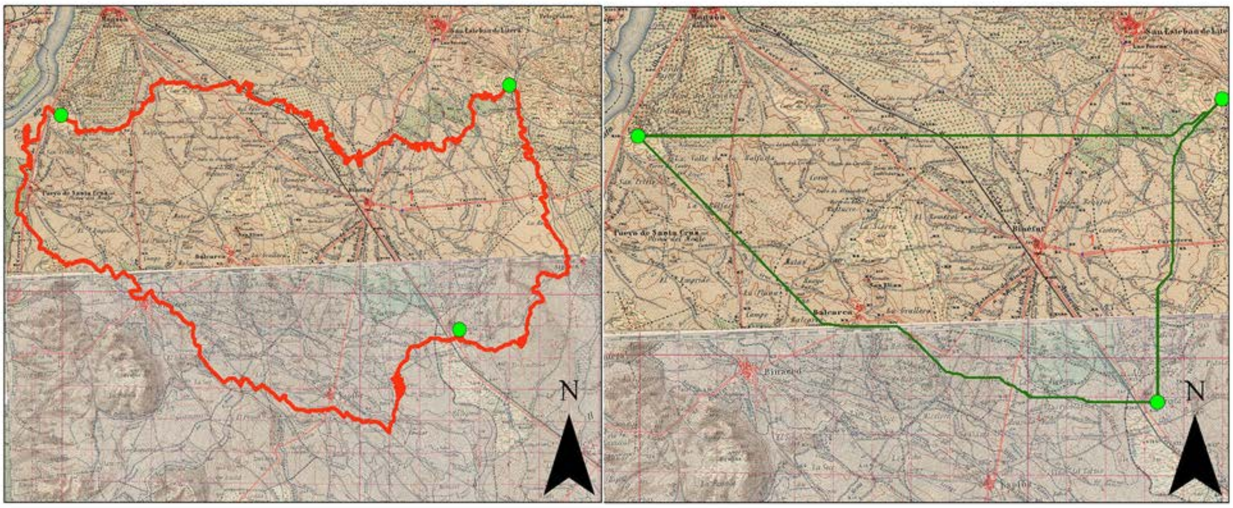

Figure 10. Result of the LCP Short range experiments among the Ilergetian settlements of Olriols (San Esteban de Litera), La Vispesa (Tamarite de Litera) and Cerro de la Alegría/Tolovs (Monzón).

cell for the short-range ones. After performing both tests we were able to note that, even cleaning up the modern features of the DEM, increasing the resolution implies a more accurate representation of the modern topography. In this way, landscape alterations such as trenches, modern agricultural terraces or embankments were represented, and can alter the layout of our LCP, for example depicting longer and more sinuous routes. Using a clear 10 m/cell DEM or a15 m/cell DEM would be more useful in order to recreate unaltered landforms. To sum up, more resolution implies more alteration, but it is necessary to remove railways and roads in order to avoid the causeway effect.

On the results obtained we can say that in view of all the above, generating LCP networks with different methods gives us clues about the structuring of the historic roads in both areas: first of all we want to point out the differences among the layout of the LCP generated with Pandolf's formula, which depicts longer paths that follow the contours, while the Hiker ones tend to describe straighter paths, they cover the shortest distance from Point A to Point B. This indicates the presence of a time-saving road structure

The application of Pandolf's formula has showed the same results in all the scenarios, this way the LCP for a single walker weighing 80 kg is exactly equivalent to two donkeys moving a 400 kg load, since the model will always tend to find the areas with a lower gradient in the DEM. In this way, the Least–Cost Path in energetic terms tends to be the same in all cases, even if it involves walking a longer distance. While Hiker's formula allows us to explain the logic behind the major roads that in some cases are still in use; in the Ilergetian case, we detected a 58% coincidence between LCPs generated with this method and the historical roads. This formula allowed us to recreate part of the layout of the Roman road between Ilerda and Osca. We were also able to find coincidences with some major cattle roads which were expressways connecting the rain-fed plains with the grazing areas.

In the Cessetan case, the long-range experiment using Pandolf's routine matched the historic, mainly the Via Augusta. However, short-range experiments show that the LCP network generated with Tobler's method has more coincidences with ancient roads. We have to note some major coincidences, such as the mediaeval roads from Valls to Nulles and Valls to Vallmoll in Cessetania.

With long-range distances there is an important difference between the results obtained in Ilergetia and those of Cessetania, due to the topography and the different method of selecting the start points. They show different behaviours, depending on whether they are natural passes or settlements. In this respect, topography is decisive when explaining the construction of the historic road networks. Cessetania has a more complicated relief, which constrains human movement, directing it towards river valleys, plains and coastal areas. This explains why the LCP calculated with Pandolf's method has more matches with historic roads, partly coinciding with the areas where movement is easy. On the other hand, the Ilergetian plain relief is a 'movement-friendly' environment and the orography is not a constraining factor. This could explain why straight paths are more efficient for moving from one point to another, and also explains the high rate of matches with historical roads obtained using Tobler's formula. In conclusion, and in view of the results, we can say that orography plays a major role in the genesis of a long-range communication network.

Besides the method used in calculating the LCPs, all these matches correspond to the places where walking or moving a load is easier, and this means they have remained despite temporal and cultural changes. However, being an optimal time-saving path or energy-saving path is not the only factor that shapes a communications network: the origin and the destination, the direction, and the settlements distribution should be taken into account.

If we compare our experience with Ejstrud (2005) study case in southern Cyprus we find that in the first, the energy equation had more matches than the time saving one, because it involves more factors. In ours, the time saving one obtains a better performance in planar areas where moving with or without load is easier, like the Ilergetia, while the energy one has more matches in harsher terrains like the Cessetan case or the aforementioned study.

Finally we want to point out that the basis of the natural corridors has been altered by their disappearance or substitution due to the new roads created by successive cultural and settlement pattern transformations, which resulted in the creation of new nuclear and peripheral areas.

Studies about the Iberian culture often tend to display only maps showing archaeological sites and rivers. With the aim of understanding the structuring of the territory we have tried to construct an approach to movement in these Iberian landscapes by comparing two well-known LCP routines. Although LCP routines have been criticised for the difficulty in computing cultural and human factors, they are useful in our study cases for answering questions about movement in the areas, as well as for understanding the logic behind movement in the Iberian territories and its persistence through time and cultures.

According to our point of view the combined use of these two routines is useful in order to identify hypothetical historic roads and to understand the logic behind them. For all the aforementioned we think that this a potential research subject to develop in further investigations

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Boundaries of Agrarian Production in the Bergisches Land in 1715 AD

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Abstract
For part of Bergisches Land east of Cologne, Germany, the maps by Ploennies finished in 1715 AD and the accompanying text provide detailed data for testing approaches used in archaeology for determining the boundaries of agrarian production. The historical maps indicate the settlement sizes ranging from single farmsteads to towns with walls. In 1715 AD the towns were quite small and the economy in this rural area relied mostly on agriculture (oats and livestock). The boundaries of agrarian production can be estimated by applying methods for allocating farmland territories to the settlement locations. The methods discussed are site catchments, retrodictive modelling for neighbourhoods, Thiessen polygons and approaches based on the distances between neighbouring settlement locations. With the exception of retrodictive modelling for neighbourhoods, two variants of the approaches are applicable, either resting on straight-line or least-cost distances.

Keywords: least-cost analysis, site catchment, retrodictive modelling, Thiessen polygons, triangulation

Introduction

For part of Bergisches Land east of Cologne, Germany, the maps by Ploennies finished in 1715 AD and the accompanying text provide detailed data archaeologists usually dream of (Figure 1). Therefore the settlement data of this rural area in early modern times can serve as a test case for checking the validity and accuracy of methods usually applied in archaeology to determine the boundaries of agrarian production.

The mathematician Erich Philip Ploennies worked as a cartographer for the rulers of the Bergisches Land. Unfortunately, in this hilly region, the Gimborn area was not part of the territory ruled by those who commissioned Ploennies' maps so that the study area consists of the two separate parts on either side (Figure 1b). Ploennies used different symbols to indicate different settlement sizes, ranging from single farmsteads to towns with walls. The data is supplemented by the Pampus list that records all settlements in the study area mentioned in historical sources before 1600 AD (Pampus, 1998). This list includes 70 settlement locations in the study area not mapped by Ploennies. However, as these locations could be identified on late 19th century maps, Ploennies probably missed them for some reason. Therefore the 70 locations were included in the case study data set consisting of 1003 settlements: In the western part covering 412 km², 749 settlement locations were recorded, for the smaller eastern part (241.6 km²) 254 settlement locations are mapped.

According to Ploennies' texts, the economy in 1715 relied predominantly on agriculture, i.e. oats, cattle and pigs. This applied even to the two towns in the study area, Wipperfürth and Radevormwald. In 1715, Wipperfürth is the biggest town with about 65 houses shown on the cityscape (Ploennies, 1715, p. 103). Although located at a crossing location of a river where three trade routes meet, Wipperfürth had hardly any trade; the economy relied on the products of the fields (*ibid*., p. 52). Ploennies also describes the landscape and economy in the administrative units covered by his maps. Amt Steinbach is located in the western part of the two Ploennies areas, north of the zone without settlements. This administrative unit had many infertile hills, no proper forest, but shrubs (*ibid*., p. 80). The wood from the shrubs was used for firewood and for manufacturing barrels. In this area, mostly oats were grown, but hardly any fruit, and cattle and pigs played an important role. The southern part of the western Ploennies area and the eastern area belong to the former administrative unit known as Amt Windeck. Also in this area mainly oats were grown, supplemented by livestock and trade (*ibid*., pp. 78–80). Ploennies mentions the stone carvers in Lindlar, but none of the mining activities and metal working recorded on the Mercator map in 1575. Most likely many people working on farms increased their income by seasonal jobs in the mines, in the small-scale metalworking industry, by collecting firewood, different handicrafts such as weaving or by other activities.

Rösener (1992, pp. 20–21) describes several improvements in agrarian technology during Medieval

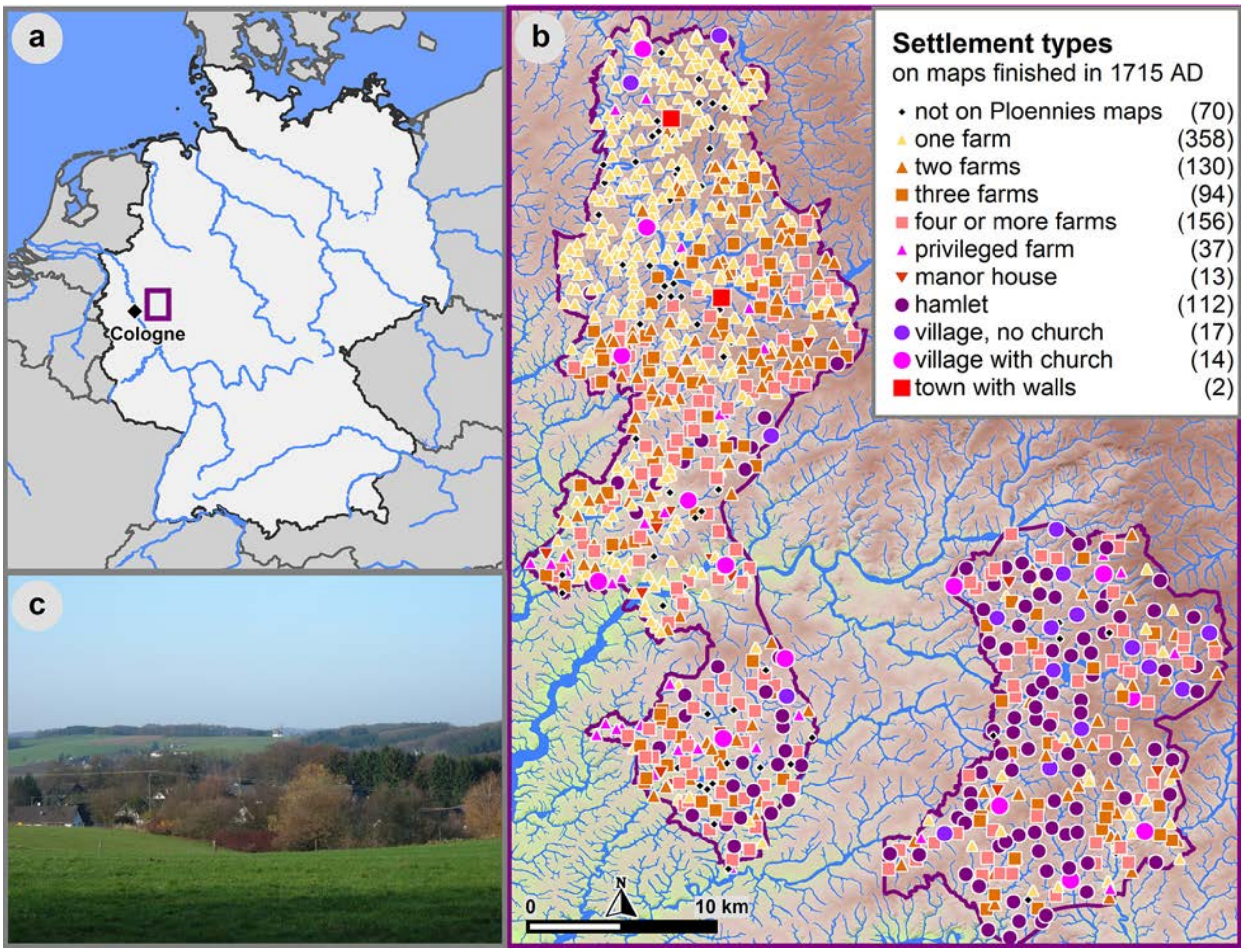


Figure 1. a — location of the study area in Germany, b — map of the study area with symbols indicating the settlement sizes recorded on the Ploennies maps, c — typical landscape in the study area.

times, such as the three-field system, enhancements of existing tools including the plough, scythe, and special yokes for horses, as well as the introduction of new crops. These advances suggest that the limits of agrarian production in historical times were even more profound limitations in archaeological time periods, with the possible exception of the Roman time period.

The settlement data in the year 1715 can be used for discussing and testing the tools in the archaeological GIS toolbox that are available for determining the boundaries of agrarian production. The tools are: site catchments, retrodictive modelling for neighbourhoods and Thiessen polygons.

In its simplest form, a site catchment is a circular buffer zone centred on the settlement (Conolly and Lake, 2006, pp. 209–225). Straight-line distances are often replaced by least-cost distances in archaeological case studies, taking the topography into account and resulting in a more irregular shaped catchment zone. The radius of the site catchment can be adjusted according to the size (or type) of the settlement.

Predictive modelling is a technique often applied in cultural resource management 'to predict the probability of archaeological settlements in unsampled landscapes' (Conolly and Lake, 2006, p. 179). Most predictive modelling studies in archaeology rely on environmental variables such as slope, distance to water or soil type. If all settlement locations are known, predictive modelling techniques can be applied to identify relevant landscape attributes for settlement locations, and for this approach the term retrodictive modelling has been coined (Herzog, 2015). In general, retrodictive modelling is only applied for point locations, but retrodictive modelling can also take the neighbouring cells in a cell-based raster into account. The neighbourhood size generating the best retrodictive result can be considered the boundary of agrarian production.

Standard Thiessen polygons, also known as Voronoi diagrams or Dirichlet tessellation, allocate territories to each settlement by dividing the area considered so that each settlement location 'is enclosed by exactly one polygon which also contains all the space that is closer to that point than any other' (Conolly and Lake, 2006, p. 211). This approach is appropriate if the landscape is fully occupied, i.e. hardly any suitable locations for new settlements are left. Replacing straight-line distances by least-cost distances is quite straight-forward, although not supported by standard GIS software (Herzog, 2013). Standard Thiessen polygons are only appropriate if all settlements are of equal size and importance. Already in 1976, a refined approach was published for creating weighted Thiessen polygons that take different population sizes into account (Hodder and Orton, 1976, pp. 187–195).

In the next sections, the potentials and limits of these three approaches will be discussed with respect to the 1003 settlements in the study area. Moreover, a method derived from Thiessen polygon properties is presented that allows the estimation of ideal population-size-dependent distances between neighbouring settlements of different sizes. These ideal distances are compared to the distances observed in the Early Modern settlement data set.

Approach 1: Site catchments

According to Conolly and Lake (2006, p. 224) the site catchment is the region that could be exploited from the settlement in question. For calculating site catchments in a GIS, it is necessary to decide on the limit of the site catchment — that is its radius measured in straight-line or least-cost distance. Wheatley and Gillings (2002, p. 160) as well as Renfrew and Bahn (1996, p. 242) refer to a paper published in 1970 suggesting a radius of 1 hour walk for a sedentary agricultural site. This radius is definitely too big for the sites within our study area, because this would result in highly overlapping catchments, even if a slow walking speed of only 3 km/h is assumed (Figure 1b).

Therefore I tried to find data on Medieval and Early Modern farm sizes in Germany. According to the study by Kerig (2008), relying on publications of historical sources as well as published ethnographic and archaeological research, the minimum farmland for growing crops is 2 hectares, and the maximum is 4 to 5 hectares if all work is carried out by humans. If oxen are available, larger farmlands of up to 10 hectares can be ploughed by the inhabitants of a single farmstead. Horses allow ploughing even larger plots, up to 33 hectares. In Kerig's view, some of the small farms without oxen can be considered as big gardens growing mostly beans, lentils or peas. Kerig's data and the figures given by Rösener fit quite well: according to Rösener (1992, p. 4), the arable land of a farmstead covered on average 2.5 to 4 hectares in the 6th to 10th century. Unfortunately, the data collected by Kerig was often recorded in regions with more favourable conditions for agriculture than offered by the study area. Moreover, in the Bergisches Land, the farmland in the past had a ring structure, centred on the farm buildings, with gardens in the ring close to the houses, followed by orchards, a zone for dairy farming, arable land and finally an extensive grazing zone (Nicke, 1995, p. 52). A similar land use structure for farms is described by Waugh (2002, p. 513). Depending on the economic focus of the farm, the size of the rings may vary, or rings might be missing. The focus of Kerig's calculations is on crops only, and therefore the figures given by Kerig provide the lower limit for the boundaries of agrarian production in the study area. A circular area covering 4 hectares has a radius of about 113 m, which is a lot smaller than the distance covered by walking for one hour — even in hilly and wet terrain. Ethnoarchaeological studies presented by Stone (1993) for group-oriented farming by the Kofyar farmers in Nigeria, suggest that the distances walked per person for group labour parties hardly ever exceeded 3 km and the distribution of distances walked exhibit a sharp drop-off beyond 750 m. So the maximum travelling distance for daily agricultural activities probably is close to walking for one hour, whereas the average distance covered is much smaller.

The catchment sizes can be adjusted in a straight-forward way to the assumption that the average farmland size of a settlement location is proportional to the number of farmsteads at that location. Keep in mind that the formula for calculating the area enclosed by a circle is $\pi*r^2$ with r the radius of the circle. Therefore the area of a circle n times this size has a radius of $r*\sqrt{n}$. So if the radius for single farmsteads has been determined, it is easy to calculate the corresponding radius of catchments for settlement locations consisting of 2, 3 or 4 farmsteads.

Nowadays, most archaeological site catchment calculations rely on least-cost distances, taking the topography into account. For the Bergisches Land a cost model is available derived from long-distance trade routes (Herzog, 2013). Costs of movement are calculated using a slope-dependent cost function with a critical slope of 13%; on wet areas or water bodies the slope costs are multiplied by 5, except at some stream crossing locations, where the multiplier is reduced to 2. Applying this cost function for allocating the site catchments results in large catchments for fairly level and dry areas, but small catchments in areas with steep gradients or wet soils (Figure 2). The costs are measured in least-cost units (lcu), with 1 lcu the effort needed to cover 1 km on level and dry terrain. In the Bergisches Land, wet soils are less suitable for farming than dry soils, and ploughing steep slopes is definitely harder than working on flat terrain. A farmer on a patch with wet soils and steep slopes can make a living if the

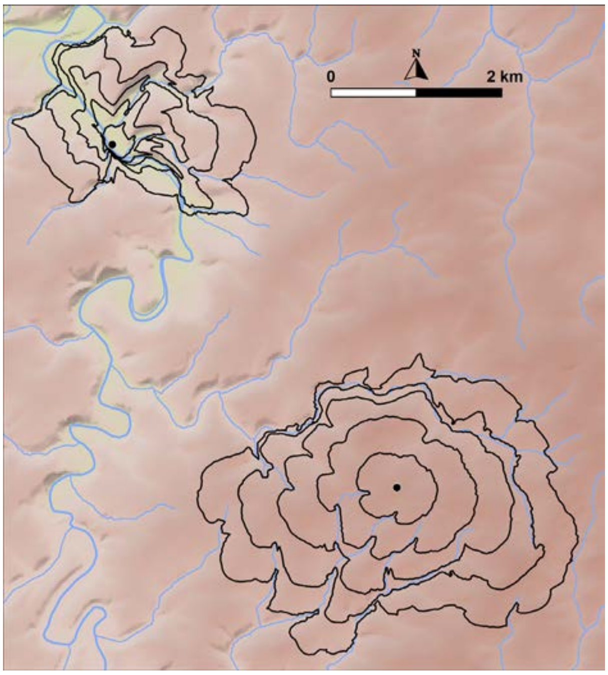


Figure 2. Site catchments with a radius increment of 0.5 lcu for two settlements in the study area: Oege in the north was a single farmstead in 1715, and Radevormwald in the south is one of the two towns with walls at that time. The area surrounding the town is fairly flat resulting in large catchments.

patch is used extensively, and therefore this farmer probably needs more land to sustain a family than a farmer working only on level and dry ground. So this is one important conclusion for site catchments: if site catchments are constructed to delimit the area used by a farmstead, straight-line distances generate more intuitive results than least-cost distances. The inverse movement cost model might create even more realistic site catchments.

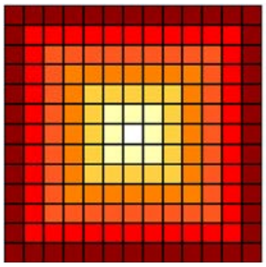
Another issue is the high density of settlements in 1715. Figure 1b creates the impression that hardly any empty patches suitable for additional farmsteads are left. This assumption is supported by the data. According to Pampus (1998, p. 85), 82% of today‘s settlements were mentioned in historical records before 1600 AD. In the study area, Ploennies' maps show 148 additional settlements that are not in the Pampus list, amounting to about 15% of the settlements recorded by Ploennies. If this assumption is true, most settlement territories share boundaries with their neighbours. Applying site catchment analysis in this situation is bound to result in overlapping catchments, but these should be avoided in view of the aim 'boundaries of agrarian production'. The algorithm for generating least-cost catchments can be modified easily to circumvent overlaps: least-cost site catchments result from spreading, starting at the settlement location, and reaching the cost limit stops this spreading process. Stopping the spreading process when another territory is met results in least-cost Thiessen polygons (Herzog, 2013). Therefore, Thiessen polygons are probably a more appropriate approach in this situation with a dense settlement pattern. Straight-line and least-cost Thiessen polygons will be discussed below (Approach 3).

Approach 2: Retrodictive modelling for neighbourhoods

The least-cost path calculations mentioned above derived costs from a DEM with a cell size of 25 m. This modern DEM is based on LiDAR data and was provided by the Ordnance Survey Institution responsible for this area (geoBasis NRW). Raster grids with a cell size of 25 m were also the basis of previous retrodicting modelling approaches, taking only the point locations of the settlements into account (Herzog, 2015). As several attributes analysed in retrodictive modelling, like slope or aspect, are derived from the DEM grid, this was an obvious choice. The settlement locations were mostly picked from a set of late 19th century historical maps which is available at a scale of 1:50,000. Although these maps are fairly accurate, it is hard to quantify the inaccuracies introduced by reading the locations from this map, because typically a single farmstead in 1715 has evolved into a hamlet consisting of about twenty buildings in 1898. So it is quite likely that the point location chosen is not within the appropriate 25 m × 25 m grid cell. This is one of the reasons why no DEM with higher resolution was used.

Previous research relying on the point locations of the settlements only found that the following environmental variables had strong impact on the choice of a settlement location: slope, soil quality, and least-cost distance to water, i.e. cells with high flow accumulation values (Herzog, 2015). Some environmental variables like slope or soil quality are not only important at the centre point of the settlement, but also for a zone of neighbouring raster cells surrounding this point. For the retrodictive modelling approach, the neighbourhood size with the highest impact on the settlement locations is an estimate for the boundary of agrarian production.

Systematic two-sample two-sided Kolmogorov-Smirnov tests for different quadratic neighbourhood sizes were performed with the freeware PAST (Hammer, 2016). Due to the raster resolution chosen, the increment in raster sizes was 50 m: 25 m × 25 m, 75 m × 75 m, 125 m × 125 m and so on (Figure 3). The grid cell averages within the neighbourhoods were calculated using the Sextante plugin of gvSIG.



radius	cells	length	hectare
0	1 x 1	25 m	0.0625
1	3 x 3	75 m	0.5625
2	5 x 5	125 m	1.5625
3	7 x 7	175 m	3.0625
4	9 x 9	225 m	5.0625
5	11 x 11	275 m	7.5625

Figure 3. Square neighbourhoods in the grid with cell size 25 m, corresponding side lengths and areas.

In the previous study, the impact of the mean slope within a catchment area covering 525 m × 525 m (6.25 hectare) on settlement location was analysed, as suggested by Ejstrud (2003). This neighbourhood resulted in a higher probability that the slope distribution of the settlement neighbourhood is random (p=5.8E-34 compared to p=1.6E-36 for point locations). Systematic tests now show that the 525 m × 525 m neighbourhood is far too big. For the slope grids, the lowest probability was achieved for the 125 m × 125 m neighbourhood (p=3.1E-41, Table 1). The result suggests that slope was most important within a 125 m × 125 m neighbourhood (1.5625 hectare) of the settlement centre. This area probably only comprises a few of the different land-use rings mentioned in the publication by Nicke (1995).

Due to the fairly large number of settlement locations, it is possible to apply this approach for subgroups, i.e. different settlement types and time periods. The subgroups tested were: (1) settlements mentioned in historical sources before 1400 AD, (2) settlements mentioned before 1500, (3) settlements mentioned before 1600, (4) single farmsteads, (5) two to four farmsteads, (6) more than four farmsteads. Four of these test outcomes are in accordance with the result for the full data set, but for the groups (4) and (5) a larger neighbourhood (175 m × 175 m, 3.0625 hectare) had the highest impact on the settlement locations.

It is not straight-forward to apply Kolmogorov-Smirnov tests to aspect data due to the fact that 0°=360° (or when considering angle measurement in radians: 0 corresponds to 2π radians). Analysing aspect classes showed that south–east aspects were preferred whereas areas with aspects in a northerly direction had fewer settlements than expected, when compared to random distributions. This led to the idea of applying the Kolmogorov-Smirnov test for the cos(α) values of the settlements, with α the aspect in degrees. The cosine is chosen instead of the sine because the main difference is expected on the north–south axis. But if the main difference is on the south–east to north–west axis, cos(α+45°) should result in a more significant test outcome. For this reason, cos(α+β) was tested for several values of β, and β=40° generated the lowest probability (p=1.2E-15). Tests with different neighbourhood sizes showed that the probabilities resulting from the Kolmogorov-Smirnov tests increased, so that point locations provided the best result.

The previous study (Herzog, 2015) also analysed the local topographic prominence of the settlements. The formula suggested by Llobera (2003) for calculating local topographic prominence (with respect to elevation) was applied. On average, settlement locations were less prominent than random locations — i.e. sheltered locations were preferred. The attribute local topographic prominence for a raster cell is the difference between its elevation and the mean (or median) elevation in its square raster cell neighbourhood. In the previous study the median in a neighbourhood of 425 m × 425 m was the basis of calculating the prominence attribute. A median neighbourhood was chosen because outliers are ignored by this approach, but systematic tests show that the mean outperforms the median with respect to the Kolmogorov-Smirnov test. Testing several neighbourhood sizes produces a minimum probability of 7.3E-43 for a 625 m × 625 m (39.1 hectare) neighbourhood. This outcome was also found for four of the subgroups defined above. The exceptions are settlement locations mentioned before 1400 and settlements consisting of more than four farms: for

Cell radius	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
hectare	0.0625	0.56	1.56	3.06	5.06	7.56	10.56	14.06	18.06
Quartiles all grid cells	8.5 13.1 19.7	9.0 13.4 19.4	9.4 13.6 19.2	9.7 13.8 19.1	10.0 13.8 18.9	10.3 13.9 18.7	10.4 13.9 18.5	10.6 13.9 18.3	10.8 13.9 18.2
KS-p	1.6E-36	5.8E-39	3.1E-41	1.1E-39	1.3E-37	1.4E-32	9.0E-30	4.1E-30	1.5E-26
Quartiles settlement locations	7.7 10.8 14.1	8.2 11.0 14.3	8.4 11.2 14.3	8.9 11.4 14.5	9.2 11.5 14.6	9.4 11.8 14.8	9.6 11.9 14.9	9.7 12.0 15.0	9.9 12.2 15.1

Table 1. Analysis of slope within neighbourhoods with increasing the cell radius: Quartiles of all grid cells and of the settlement locations; Kolmogorov-Smirnov probabilities (KS-p). Cell radius 2 produces the lowest probability.

these subgroups, larger neighbourhoods (675 m × 675 m) produce a lower probability.

Combining the results for slope, aspect, distance to water and prominence, the ideal location of a rural settlement in 1715 is in a natural depression shaped like half of a bowl with a radius of 300 m, with a fairly level area (radius of about 60 m) surrounding the farm buildings, and a small creek running close to the farm buildings down in southeast direction, the bowl part of the landscape is in northwest direction. This fits well with Nicke's description of early settlements in the Bergisches Land (Nicke, 1995, p. 49). For settlements consisting of more than four farms, the diameter of the bowl is somewhat larger, and for settlements with four farms or less, the level area surrounding the buildings is larger as well.

So the retrodictive modelling for neighbourhoods approach combined with other predictive modelling techniques generates quantitative results with respect to the settlement pattern and the boundaries of agrarian production. But this approach also has some drawbacks. The calculations are fairly time-consuming if performed for several neighbourhood sizes and the six subgroups mentioned above. This is one of the reasons why the neighbourhoods of the relevant attribute soil quality were not analysed. For the important attribute 'distance to water bodies' considering the distance to the settlement itself suffices, there is no benefit when including the neighbourhood.

The square neighbourhoods with side length increments in steps of 50 m are not quite appropriate. Unfortunately, disk-shaped neighbourhoods are not supported by my GIS software. With regard to the ring structure of land use mentioned above, a refinement of the approach might try to identify weights of the landscape attributes for the different zones. For instance, the slope of orchards is probably less important than that of arable land.

Approach 3: (Least-cost) Thiessen polygons

Thiessen polygons have been used for a long time in archaeological spatial analysis (for a short history see Wheatley and Gillings, 2002, p. 149). A group of archaeologists at Cologne University use standard Thiessen polygons to determine the typical territory allocated to a settlement or cemetery in areas where a complete sample was identified with high reliability, for instance due to archaeological research preceding open cast mining (e.g. Wendt and Zimmermann, 2008; Wendt *et al.*, 2012). They apply this approach to settlement and cemetery data from different periods including prehistorical, Roman and early Medieval times. For instance, Wendt and Zimmermann (2008) study the size of the Thiessen polygons of 2nd century Roman villa sites. For the loess area east of Cologne with more favourable soils than in the Bergisches Land, Wendt and Zimmermann calculate for two separate areas a mean density of 0.8 (Hambach) and 1.7 (Aldenhovener Platte) villa sites per km^2 respectively. These figures correspond to average villa territories of about 125 (Hambach) and 59 hectares (Aldenhovener Platte). Thiessen territories with a mean size of about 500 hectares were calculated for villa sites in two regions south of the Bergisches Land in Germany (Wetterau and Neckargebiet).

The average size of the standard Thiessen polygons in the study area is 62.2 hectare when omitting the polygons clipped by the study area boundary. The size of these standard Thiessen polygons varies between 6 and 309 hectares. The standard Thiessen polygon approach has been criticised because it is a 'solely geometric allocation method and, as such, it assumes that the social and geographic features of an area have no impact on the allocation of space' (Wheatley and Gillings, 2002, p. 151). It is for this reason that Wheatley and Gillings advocate the application of cost surface modelling (cf. Figure 5a).

The least-cost Thiessen polygons for this study area were already shown in a previous publication (Herzog, 2015). The mean size of these territories is slightly smaller than with the standard Thiessen approach (61.2 hectares), the range of sizes is 3.2 to 354 hectares. The standard and least-cost Thiessen polygons calculated for the settlement locations in the Bergisches Land do not take the importance or size of the settlement into account. Therefore it is quite surprising that the median of the least-cost territory size increases with settlement size, with the exception of the class comprising villages and towns (Herzog, 2015). This also applies to the median sizes of the standard Thiessen polygons (Figure 4). In general, standard Thiessen polygons should only be created for settlements of equal rank (Renfrew and Bahn, 1996, p. 171).

Connecting neighbours

As mentioned above, Hodder and Orton (1976, pp. 187–195) published a method for generating straight-line based Thiessen polygons taking the population size into account. Their idea is based on the fact that Thiessen polygons and Delaunay triangulations are closely related. With traditional Thiessen polygons two settlements are neighbours if they share a common boundary line. The graph resulting from connecting all neighbours is known as Delaunay triangulation (Wheatley and Gillings, 2002, pp. 149–150). If such a triangulation line connecting two neighbours crosses the common Thiessen territory border, the line is cut by the border into two parts of equal length (Figure 5b).

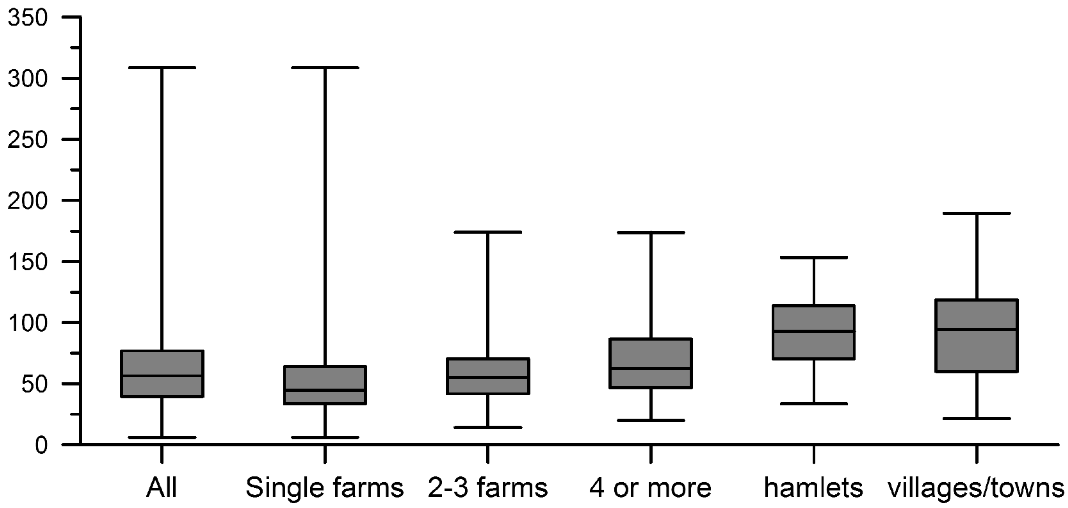


Figure 4. Median standard Thiessen polygon sizes increase with increasing settlement size.

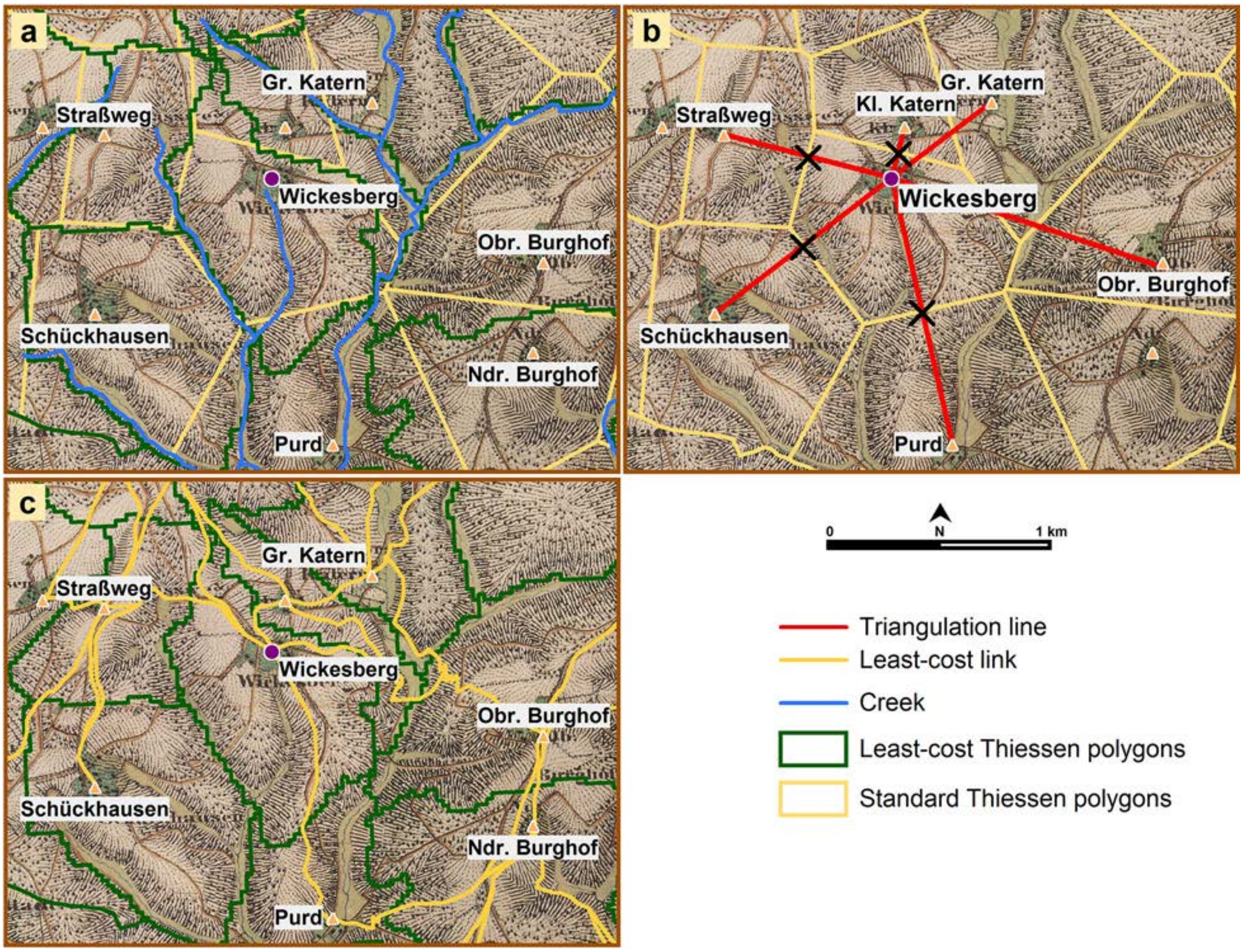


Figure 5. Settlements on the map created 1715, symbols as in Fig. 1b, map created in 1844 in the background; a — comparison of least-cost and standard Thiessen polygons; b — straight-line triangulation lines and standard Thiessen polygons; c — least-cost links between neighbours and least-cost Thiessen polygons. The link between Purd and Schückhausen is missing because both corresponding polygons are clipped by the study area boundary.

The idea of Hodder and Orton is to select the cutting point taking the population sizes into account. For instance, if settlement A has four times as many inhabitants as settlement B, the ratio of the two line segment lengths is 2 to 1. As mentioned above, the circle of radius 2 is four times as big as the circle with radius 1, therefore the square root transformation is required for calculating the cutting point (Figure 6).

Another analysis of triangulation lines connecting neighbouring settlement locations was presented by Siegmund (2009). His study relies on the fact that if these points are totally ordered, all corresponding Thiessen polygons are of equal size, and the length of the triangulation lines is constant as well. If a settlement location is missing in this regular distribution of points, the triangulation lines in this area are twice as long. Based on this observation, Siegmund creates the histogram of triangulation line lengths and checks the peaks. The triangulation line length corresponding to the highest peak is considered the typical distance between two settlements. If another peak is found at twice this distance, this is an indication of missing settlements (see also Wendt *et al.*, 2012, pp. 271–275). So according to Siegmund, the analysis of the triangulation line lengths can be used to predict the location of settlements missing in the archaeological record.

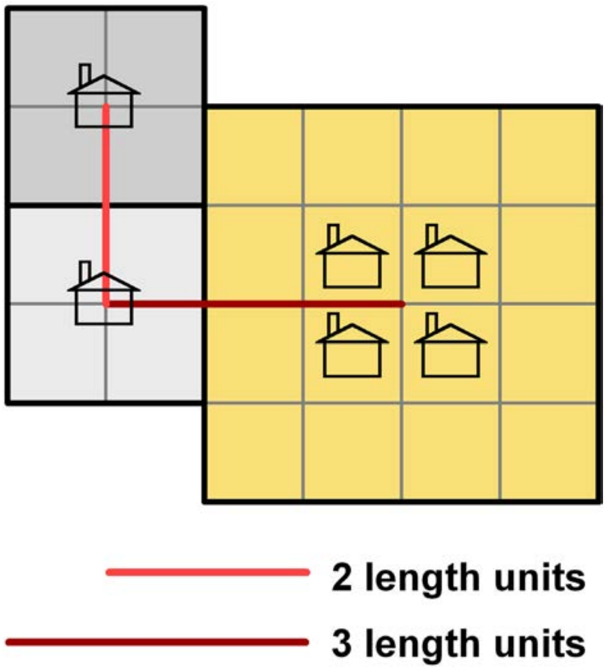


Figure 6. If the territory size of a settlement consisting of n farmsteads is n times as big as the territory of a single farmstead, and the distance between two single farmsteads (left) is two length units, then the expected distance between a single farmstead settlement and a settlement consisting of four farmsteads (right) is three length units: √1 + √4.

Inspired by these publications, the triangulation lines between neighbouring settlements in the study area were constructed as well as the least-cost connections between neighbours. Only those connections are included in the analysis where one of the neighbours is located in a polygon not clipped by the boundary of the study area. This results in 2057 least-cost connections between neighbours. This data set is a lot bigger than the 754 least-cost polygons not clipped by the study area boundary. Moreover, some data of settlements close to this border line is included. However, neither the data set consisting of the Thiessen territory sizes, nor the lengths of the (least-cost) connections between neighbours are independent observations and this complicates statistical analysis.

The largest class of least-cost connections between neighbours consists of the links between neighbouring single farms (n=486). The histogram of the link lengths for this class shows a unimodal, but skewed distribution (Figure 7). Some links are more than twice as long as the typical (median) link length of 1.19 lcu. As mentioned above, only a very few of the modern settlement locations are missing on the maps finished in 1715 AD. This led to the hypothesis that these gaps can be found along the very long links. However, checking these long connections on a historical map showed that these long least-cost links are mostly detours visiting other settlement locations before reaching the target settlement, therefore the hypothesis is rejected. Incidentally, most of the long connections checked coincide quite well with the paths depicted on the historical map created in 1844 (Figure 5c). Deviations of the paths on this map from the calculated paths can often be attributed to the fact that not all favourable locations to cross water bodies are included in the cost model.

Another hypothesis is that soil quality has an impact on the length of the least-cost link between neighbours. The lower the soil quality, the more farmland is required to sustain the people living in the farmstead, because in general, high quality farmland produces more calories per hectare. With the Vertical Mapper plugin of MapInfo, it is possible to calculate the mean soil quality of a polyline by sampling the line at 100 equidistant locations. Using this function, the soil quality of all links between neighbouring single farmsteads was estimated and compared to the length of the links. With least-cost distance links, the correlation with the soil quality is -0.033, with straight-line links, the correlation is -0.155, so there is only very weak evidence to support the hypothesis that soil quality has an impact on territory size (Figure 8).

The approach of Hodder and Orton mentioned above can be modified to predict the length of the triangulation

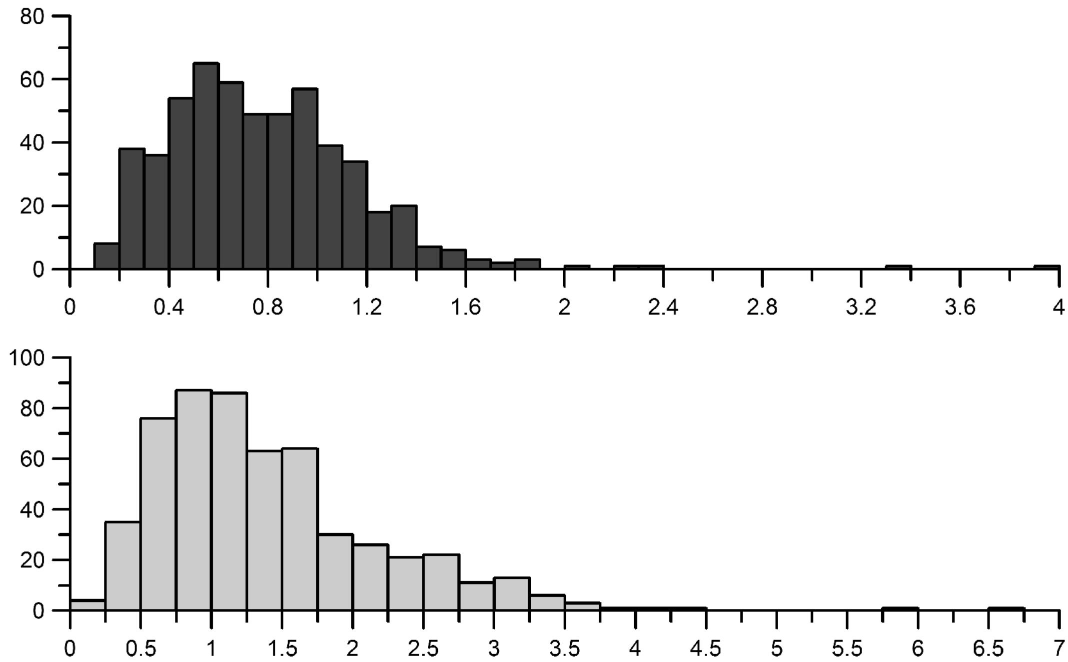


Figure 7. Histogram of link lengths between neighbouring single farmsteads: top — straight-line distances (km); bottom — least-cost distances (lcu).

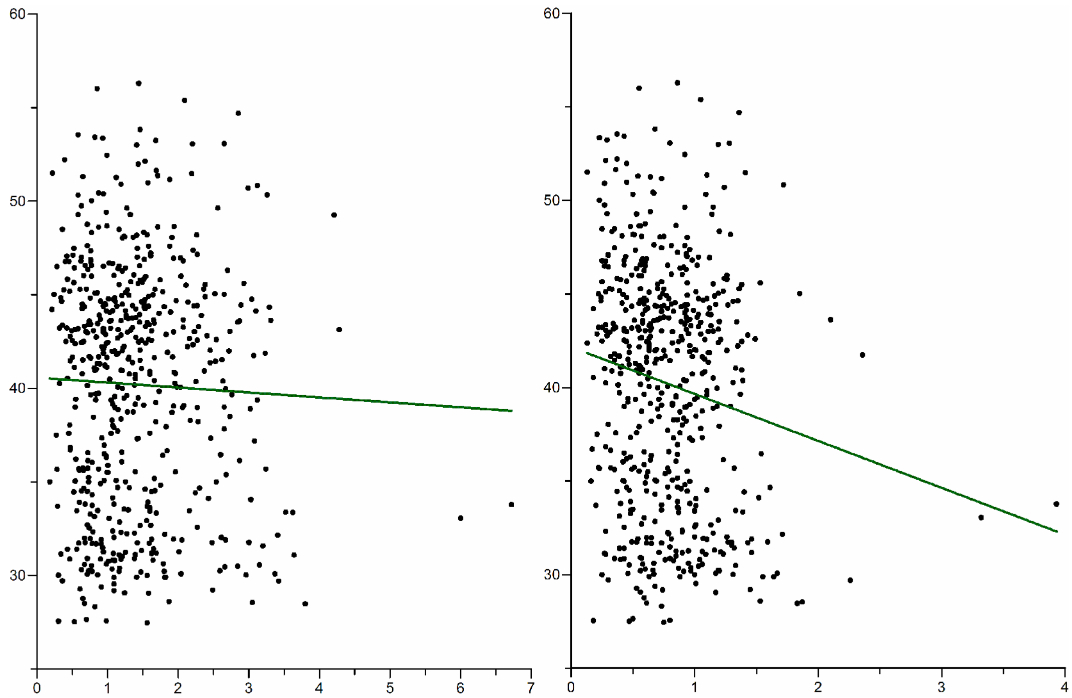


Figure 8. The scatter plots show the soil quality on the y-axis and the link length on the x-axis, left: least-cost links measured in lcu; right: straight-line links, given in km. For both scatter plots the green regression line is drawn.

links if the territory area is proportional to the number of farmsteads on the territory. For instance, if the typical distance between two single farms is 2 units, the predicted distance between a single farmstead and a settlement comprising 4 farmsteads with a territory four times as big as that of the single farmstead is 3 units (Figure 6). The predicted distances are compared to the median observed distances for each link type between neighbours with known number of farmsteads. For straight-line distances the correlation between these two variables is a lot higher (0.8) than for least-cost distances (0.4). The lower correlation for least-cost distances probably is related to the fact that least-cost distances allocate a small territory to farmsteads on steep slopes or wet soil though such farmsteads need more farmland for extensive agriculture than farmsteads on less problematic locations.

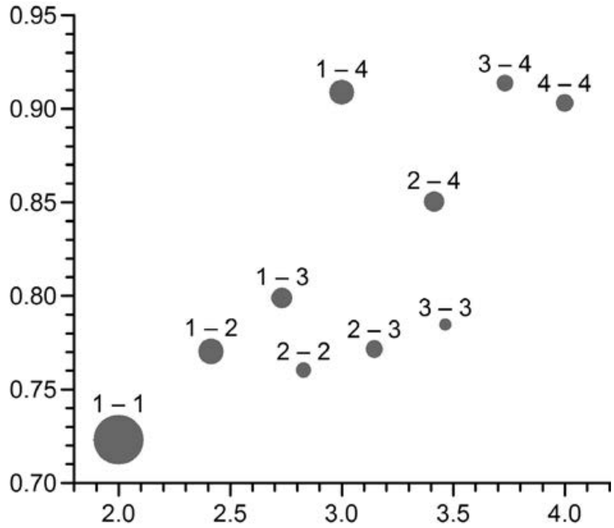


Figure 9. The scatter plot compares the predicted distance with the observed distances for the settlement locations where the number of farmsteads is known. The units on the x-axis are the expected distances, the y-coordinates are the medians of the straight line distances for each link type between neighbours with known number of farmsteads. The bubble size indicates the number of links for this link type.

Figure 9 shows the close relationship between the predicted and the observed distances for the settlement locations where the number of farmsteads is known. The labels indicate the number of farmsteads in source and target location of the links. The straight-line medians for links to neighbours with 4 farmsteads (bubbles with labels 1-4, 2-4, 3-4, and 4-4) are greater than expected, but checking the legends of the Ploennies maps reveals that the corresponding symbol was used for 'four or more farmsteads'. Therefore this observation is in agreement with the size prediction model. The scatterplot also shows that the neighbour links of single farmsteads (bubbles with labels 1-1, 1-2, and 1-3) are on a straight line with steeper slopes than the neighbour links of settlement locations comprising two farmsteads. Retrodictive modelling of the single farmsteads already found that single farmsteads are in general somewhat different from the rest of the settlement locations (Herzog, 2015), and this is again supported by the results presented in Figure 9.

The median of the links between single farmstead locations allows estimating the size of the typical territory of such a farmstead: for regularly distributed farmsteads of equal size the Thiessen polygons are hexagons of equal size. The area of a hexagon with side length t is given by $1.5 * t^2 * \sqrt{3}$, and the distance between two neighbouring farmsteads is $t * \sqrt{3}$. So the median distance of 723 m results in a hexagon size of 45.3 hectare. The median distance of neighbours comprising two farmsteads is 785 m, corresponding to a hexagon size of 53.3 hectare. So, in general, the territory size increases with the number of farmsteads in the corresponding settlement location, but territory size and number of farmsteads are not proportional. Therefore, the method of Hodder and Orton is not appropriate to delimit the territories. The size of these territories is within the range published for the Roman villa sites (see above) and well above the sizes of farms cultivating crops only discussed by Kerig (2008).

Conclusion and future work

A complete sample of settlements in a pre-industrial rural area allows testing and refining the approaches in the archaeological GIS toolbox for determining the boundaries of agrarian production. The sample consists of 1003 settlement locations, in a study area covering 653 km² in a hilly terrain with lots of creeks. However, the set of settlement locations is not uniform, and different settlement types cluster in different parts of the study area. This complicates the analysis, and so this study presents only intermediate results. Retrodictive modelling partly based on square raster grid neighbourhoods identified and quantified one of the settlement types described by Nicke (1995, p. 49). These settlements are located in a natural depression shaped like half of a bowl with a radius of 300 m, with a fairly level area (radius of about 60 m) surrounding the farm buildings, and a small creek running close to the farm buildings down in southeast direction. But according to Nicke, other settlement types existed as well, although their number is limited. Additional research is needed to check if it is possible to classify the settlements according to their landscape attributes.

The average Thiessen polygon area is a lot larger than the most relevant sizes of the square raster grid neighbourhoods and the farm sizes found by other scholars. This may be explained by the land use ring structure for each farming settlement proposed by Nicke. The land use rings suggest that the intensity of land use diminishes with (least-cost) distance from the centre. The distance decay function for the travelling distances of Kofyar farmers is evidence of an intensity decrease on another scale. Often it is not possible to draw clear-cut boundaries, and fuzzy boundary buffers are more appropriate in this case.

A distance decay function is also the basis of Xtent modelling (Renfrew and Bahn, 1996, pp. 171–172; enhanced and implemented by Ducke and Kroefges, 2008) that allocates territories taking the size of the centres and their distances into account. The distance decay function implemented by Ducke and Kroefges is linear, but adjusting to another function is straight-forward. The Xtent algorithm allows us to model dominance, i.e. 'the territory of the smaller site is simply absorbed [...] into that of the larger one' (Renfrew and Bahn, 1996, p. 171), but depending on the parameters chosen, unallocated areas may result. For delimiting the boundaries of agrarian production, overlapping territories of the settlements consisting of one or a few farmsteads are not appropriate. Therefore neither the Xtent model nor the Christaller models (Renfrew and Bahn, 1996, pp. 171–172; Waugh, 2002, pp. 406–410) were considered in this study. However, it seems that Ducke and Kroefges modified the Xtent algorithm so that overlaps are avoided. Applying this algorithm with various parameters for the settlements in the study area might therefore generate useful insights.

The attempts to delimit the territories of the settlements provided evidence for the assumption that least-cost distances produce less intuitive territories than straight-line distances. Farms with more favourable conditions for agriculture generate more calories per hectare so that a smaller territory is needed. However, the soil quality and the territory size hardly correlate at all for the single farmsteads in this data set. This analysis used the fact that the link length between neighbouring settlements of equal size can be considered as a proxy for the territory radius. Territory radius increases with the number of farmsteads, but is by no means proportional to this number. Including some of the features on the Ploennies maps like forests and mills in the analysis might improve the results, i.e. reduce the large variation in the lengths of the links of two given settlement classes. Additional data on the agriculture of 1715 is needed to create more realistic models. For the year 1828, more detailed data concerning land use and inhabitants is available for the study region (referred to by Wendt *et al*., 2012, pp. 293–303), but it seems that the economy of this area had changed by then. According to the study by Wendt *et al.*, crops had to be imported into this region at that time, and textile production played an important role. On the basis of more complete data, it might be possible to reconstruct the settlement processes in the study area by agent-based modelling.

Acknowledgements

The author is grateful to one of the anonymous reviewers who provided many suggestions for improving the paper. Due to time limitations, only some of the issues are addressed in the final version of this paper. In the future, these other issues will most likely trigger additional research.

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Mieko Matsumoto and Espen Uleberg (eds) 2018. ***CAA2016: Oceans of Data***
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
Oxford: Archaeopress

Geometric Graphs to Study Ceramic Decoration

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Abstract

As with geography, ceramic decorations are essentially spatial organisations of features. Therefore, they should be analysed with spatial indexes. But spatial analyses, at the shard or the complete ceramic scale, are often difficult to set up, mostly because of the contiguity of graphical features.

This paper presents a new method to record and analyse ceramic decoration. We use graph theory, with a GIS interface and Python programming, to analyse ceramic decoration in a bottom-up process. A priori definitions are minimal and only concern elementary units (morphological, graphical and plastic) which compose the ceramic.

The studied corpus is composed of ceramic decorations belonging to the Mailhac I facies (Late Bronze Age), characterised by complex figurative compositions. Each decoration — complete or fragmented — is considered as a spatialized network (i.e. geometric graph). Graph theory provides tools to record and measure proximities between units and normalised indexes to compare different decorations, whatever their completeness. The GIS offers a graphic interface and ensures the correctness of spatial relationships between these units. The typology of these units is realised in a hierarchical oriented graph. This structure allows processes of generalisation (going up the tree) and specification (going down the tree), permitting comparison between units with different kinds of resolution and/or complexity. The method presented here can be used for other types of mediums (statuary, rock art, etc.).

Keywords: ceramics, decorations, network analysis, graph theory, GIS, python

Introduction

Theoretical background

Due to their abundance in archaeological layers (often as shards) and their short life span (Demoule, 2009), ceramics have, since the beginning of archaeology, represented one of the most detailed typological series of Later Prehistory (Neolithic to Iron Age) and more broadly of pre-industrial societies. While generic forms of ceramics (defined by the maximal aperture, height, width and width of the wall) depend on their functions (store, cook, consume) and show typological convergence through time and space, a large degree of freedom is allowed in the addition of plastic elements (pedestal base, carination, rolled rim, etc.) and decorations (vertical grooves, roll-wheel impressions, colours, etc.). The isochrestic variation (Sackett, 1990) assumes that the more complex an artefact is, the less likely it is that two different cultures use the same combination to reach the same result. The respective choices, within a tradition, are synonymous of the notion of '*style*'. These '*styles*' have a classificatory value (etic value) and a potential emic value that participate to the identification of cultural facies (Le Quellec, 1998), even if the granularity of these facies is variable (Dietler and Herbich, 1994). Ceramic decorations, because they are largely disconnected from technical constraints, are data of prime importance in recognising different '*styles*'.

Despite their omnipresence in archaeology, decorations are still relatively unexploited; multivariate analyses are often the culmination of the statistical process and spatial analyses of graphical patterns is commonly scarce (see for example Desenne, 2003). At the graphical units level (the thinnest elements of the decoration), typologies are usually developed with families (or types) divided into varieties (or subtypes). But, the gathering of graphical units into one — rather than another — family is often empirical, especially for schematic shapes. Furthermore, the proximities *between* these families (inter-variability) and *within* these families (intra-variability) are generally not calculated (Figures 1 and 2).

Van Berg (1994) proposed a methodology, inspired by linguistics, to study decoration of Linear Pottery

composition level	description
patterns	organisation of graphical units
figures	organisation of patterns
decorative scheme	organisation of figures

Table 1. Schema of Van Berg's grid of analysis for the different levels of composition of graphical units in the decoration (after Van Berg, 1994). The decorative scheme is the decoration.

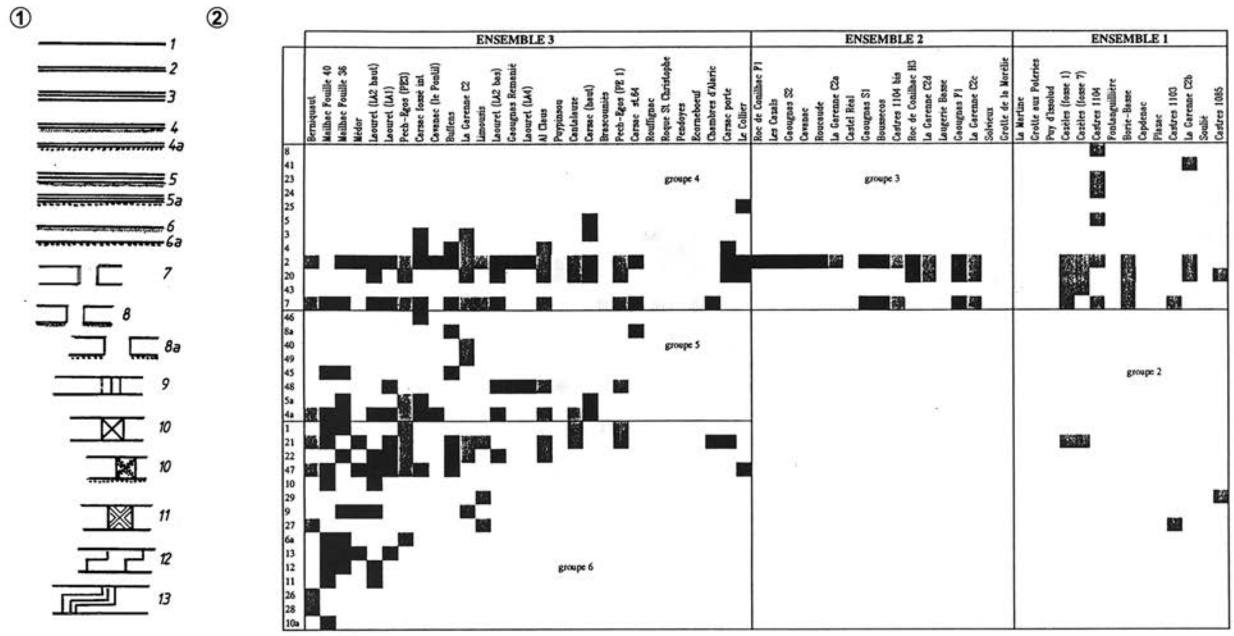

Figure 1. Seriation of ceramic decorations in the South of France during the Late Bronze Age (after Carozza, 1997, detail). (1) Most basic elements considered, graphical units ('stairs', 'lines', 'crosses', etc.), are already a grouping of geometrical shapes. Inter-variabilities between these groups of decorations are not evaluated. (2) Seriated data frame based on presence/absence of these groups of decorations.

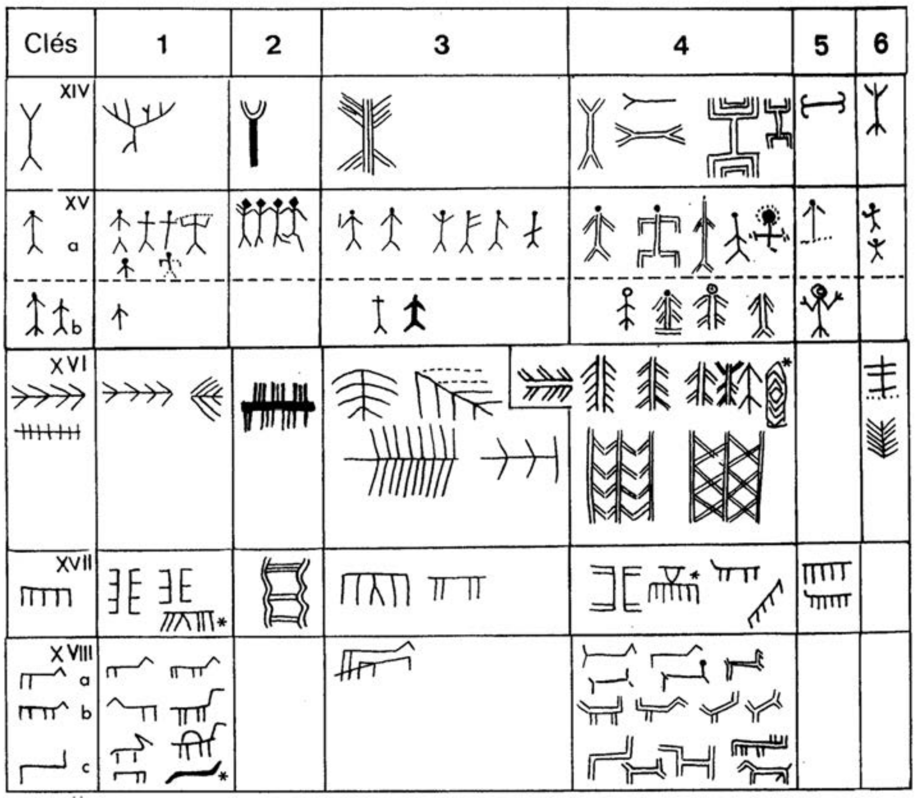

Figure 2. Typological data frame of the decoration units (after Gómez de Soto, 2003). Each row represents a type (xiv: stick signs with bifid extremities, xv: anthropomorphic, xvi: barbed signs, xvii: pectiniform signs, xviii: zoomorphic). Each column represents a regional variation of this type (1: Rhone region, 2: Bourget lake, 3: Western centre, 4: Languedoc and Catalonia, 5: Massif Central, 6: East of France). In each of the frame's cells (for ex., cell xiv, 4), variability of the type is illustrated by examples. Intra-variabilities within a cell, and inter-variabilities between cells of the same row, are not calculated.

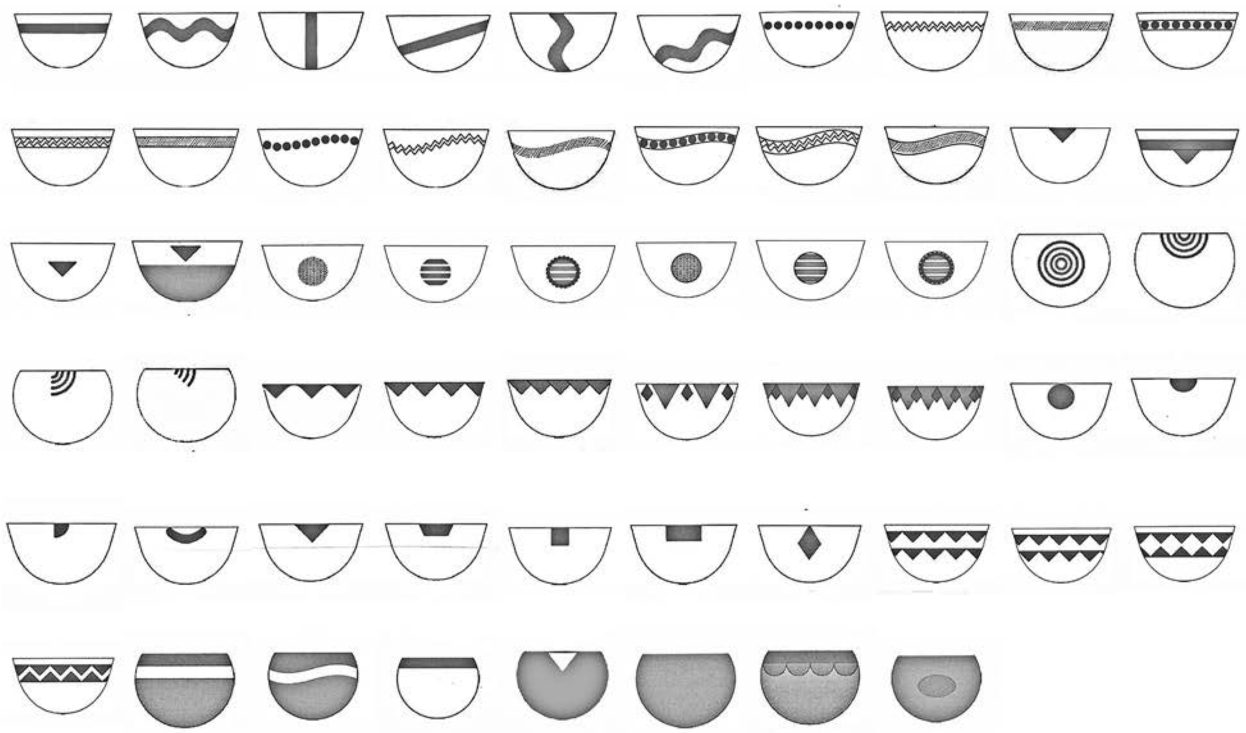

Figure 3. Compilation of Gallin's typology of Kobadi's ceramic compositions (after Gallin, 2011). Definition of a priori classes leads to a considerable amount of descriptions at all levels, for motifs (patch pattern, line pattern, weave pattern, etc.), figures (banner, ribbon, pendant, inset, coverage, etc.) and location (near the rim, on the neck, on the upper part of the belly, etc.). A consequence is the massive use of infographic to schematise all cases; the archaeologists cut themselves off from the source drawings during the analysis process. Once again, definitions of the decoration's location on the ceramic surface remain also largely qualitative; relations between different spatial configurations are not calculated.

ceramics (LBK culture). However, application of this methodology to these ceramics only led to qualitative results. Van Berg considers two levels of analysis: the study of graphical units and the study of organisations of these graphical units. The first are likened to a vocabulary, the second to syntax or grammar (Table 1).

In France, Van Berg's 'systemic' methodology has inspired various scholars, who developed quantitative approaches to study ceramic decorations (among others Gallin, 2011; Manen, 2000). But in these studies, the schematism of graphical units, the difficulty of characterising them, the variability of decorations and the fragmentation of ceramics have represented real obstacles. For most detailed analyses, application of this methodology, or a similar methodology, has led to tedious descriptions and overly numerous categories, with high probabilities that most of them will be represented by a unique element (Figure 3).

As said previously, definition of different levels of organisation for graphical units was inspired by structural linguistics. At first, this distinction was useful to study rock art, like Palaeolithic cave paintings (Leroi-Gourhan, 1992) but, despite its theoretical interest, this approach is, in practice, not adequate. Language and writing (subjects of linguistics), are linear sequences of semantic units. This linear sequence is known as the 'syntagmatic axis' where units follow each other (in column, in line, in boustrophedon, etc.) while the 'paradigmatic axis' refers to the signifiers of each of these units. Graphical units have spatial relationships that spread in different directions, and not only linearly. Whereas spatial analyses can be difficult to implement, due to the need for measurements (distances, directions, etc.), graph theory offers a heuristic tool to study ceramic decorations.

Research questions

We principally applied the tool to the decorated ceramics of Mailhac I, a Late Bronze Age facies (Bronze final IIIb, ca 900–750 BC) concentrated in the South of France (Languedoc) and North–eastern Spain (Catalonia). This ceramic facies is characterised by rectilinear geometrical and figurative decorations realised with a double tip instrument. Similar decorations, made with a single tip, occur also in France (Western centre and East). The semantic complexity of some of these decorations has led to hypotheses linked to a probable narrative function of the decoration: a mnemonic means to preserve myth structures (Zipf, 2006) or social

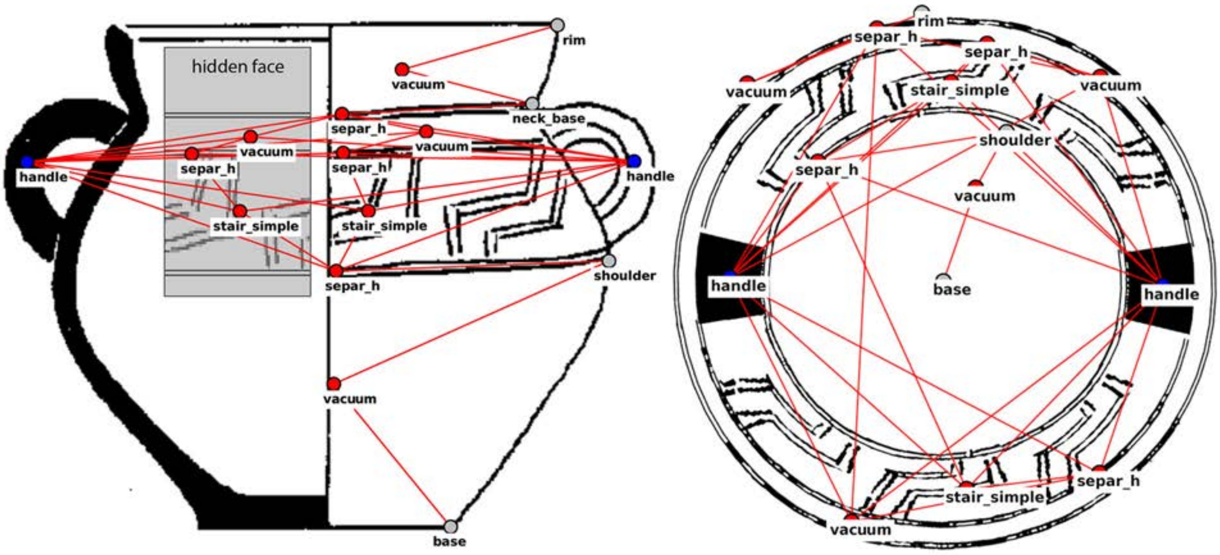

Figure 4. Equivalent graphs for the decorated ceramic from tomb 17 of Le Moulin necropolis, Late Bronze Age (Aude, France). Original document where only a quarter of the ceramic surface is presented (left, side view) and supposed topview from the same document. The 'stair' is assumed to be present six times on the whole ceramic (right, top view). Red nodes: graphical units; grey nodes: morphological units; blue nodes: plastic units).

schemes (Gómez de Soto, 2003). Comparisons with hieroglyphic and alphabetic writings have also been made (Nicolas and Combier, 2009).

Figuration (anthropomorphic, zoomorphic, etc.) appears in those regions, while ceramics of the rest of the European Bronze Age and the Early Iron Age are largely aniconic. The reasons for this reappearance are still poorly understood (Carozza, 1997). According to some scholars, the Mediterranean domain could be the inspiration for these figurations (Guilaine and Py, 2000), while others look towards the cultures of the North-Alpine Rhineland-Palatinate, Switzerland and eastern France (RSFO) (Gómez de Soto, 1993) and some consider them as a local innovation (Zipf, 2006). The arguments — based on the existence of identical graphical units, forms of ceramics, etc. — for each of these hypotheses are equally valid,and so the cause of this reappearance remains unresolved. Furthermore, it is quite probable that no help will come from the cross-dating of the elements of material culture (the chronological limits of 'cultures', 'facies', 'periods', etc. are too imprecise to detail this brief event), nor from the refinement of radiocarbon dating (the period partly belongs to the 'Hallstatt plateau'). Therefore, to progress in the understanding of the reappearance of figuration, we privilege an analysis of the semantic information firstly based on the signifiers. The purpose of our research is to go deeper in the identification of styles and typo-chronology by understanding filiations (predecessors, parentage, etc.) of ceramic decorations.

Data and case study

The development of the methodology has been done principally on the ceramic decorations coming from the necropolis of Le Moulin (Aude, France) in West Languedoc. Excavated during the fifties, the ceramics of the necropolis are actually inaccessible. We were able to work only from drawings and descriptions, which were not always precise, particularly concerning the presence and situation of coloured pigments (red, white) in the decoration. In the monograph of the necropolis (Janin *et al.*, 1998), drawings of ceramic decoration were not explicit concerning the total number of units present on the ceramic. We assume the information on which this reproduction is done by the archaeologist is sufficient although, in some cases, information has had to be extrapolated from drawings (Figure 4).

Geometric graph, a heuristic for ceramic decoration analyses

Graph theory (i.e. network analysis) offers a vocabulary and a conceptual framework to deal with notions of networks, relationships and neighbourhoods. A system can be represented by nodes connected (or not) to each other with edges. Each decoration, complete ceramic or shard, is considered as a graph. Each node, called here a unit, has a type (for example, horse, vacuum, handle, etc.) belonging to the decoration (plastic and graphical units), or to the shape (morphological units) of the ceramic. Relationships between units are modelled

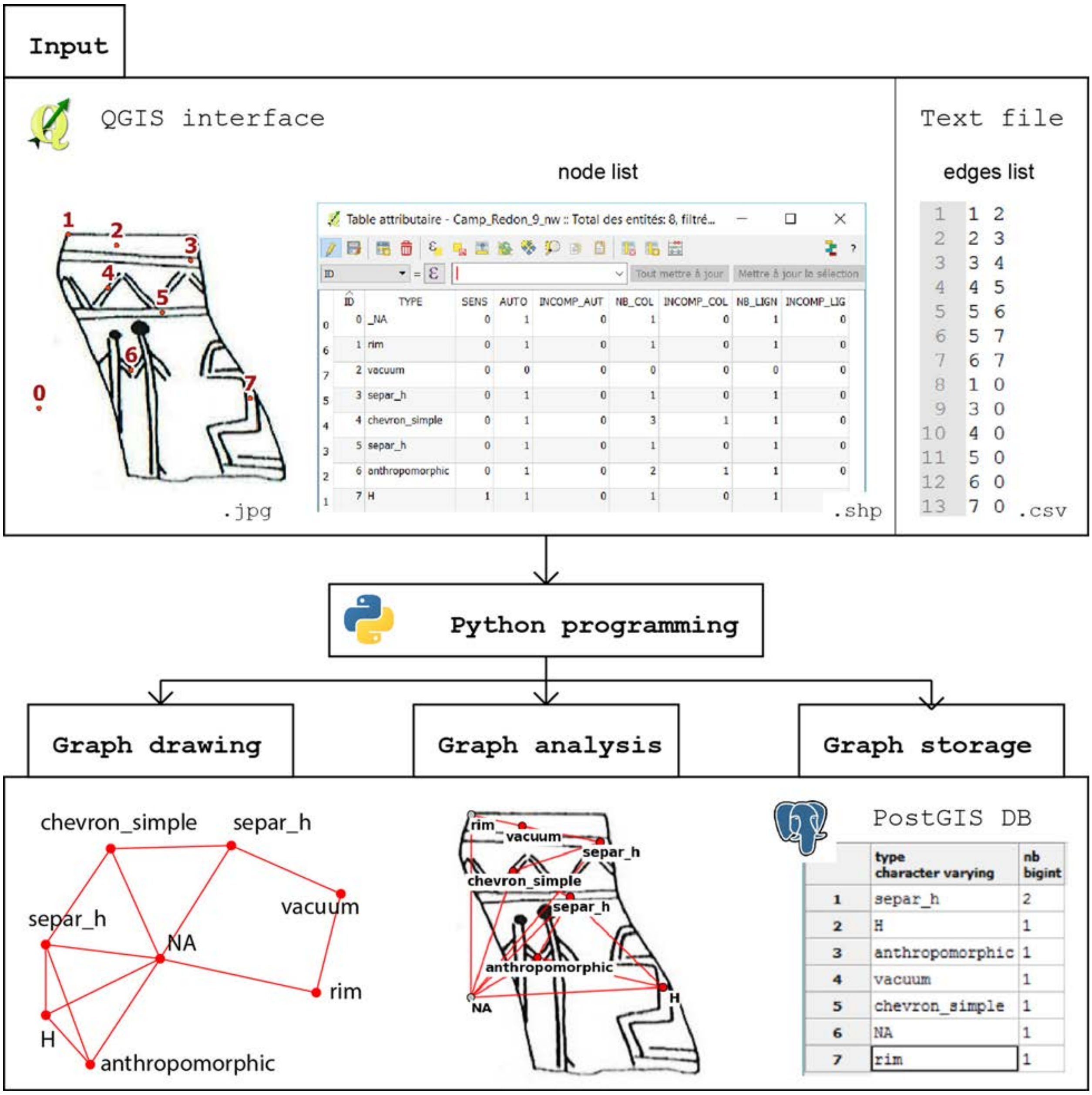

Figure 5. Schema of the workflow. The GIS interface (QGIS) permits us to maintain a permanent link with the original decoration. The Python libraries used to manage the layer of nodes (a shapefile) are mostly 'ogr', 'fiona' and 'shapely'. The text file, where edges are recorded, is managed with the 'csv' library. The drawing of the decoration, a raster file, is managed by the 'Image' library. The graph is created and analysed with the 'networkx' library. Connection with the PostGIS database, to store data, is handled by the 'psycopg2' library.

qualitatively: an edge exists between two nodes when they are close one to the other (see below). At first, there is no need to know precisely the centimetre distance and azimuth between two or more units. An important piece of information is the understanding of the neighbourhood of a given unit. Secondly, measurements between units can be calculated in the GIS (scaled and oriented).

According to Tobler's spatial fundamental law, 'everything is related to everything else but near things are more related than distant things' (Tobler, 1970). In graph theory, Tobler's 'everything' is the graph itself with its global indexes (connectivity, distribution of connections, etc.), equivalent in geography to Second Order Neighbourhood Analysis, while the 'near things' are local indexes of nodes and edges (locations in the graph, neighbourhoods, etc.), and equivalent to First Order Neighbourhood Analysis.

Nodes are spatialized in the GIS as a shapefile (.shp) of points. In parallel, a list of connections between these

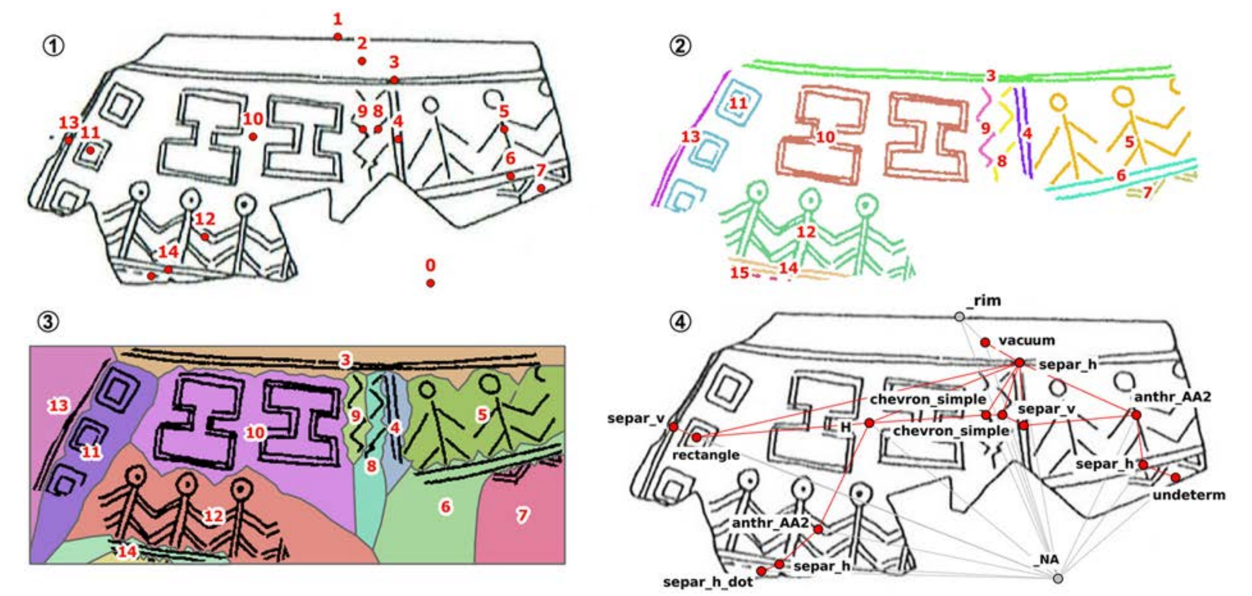

Figure 6. Complete process of composition recording for a decorated shard from Tonnerre I (Hérault, France), Late Bronze Age. 1: Opening of the drawing in QGIS and recording of the graphical units as a shapefile of points; 2. Vectorisation of the drawing (a raster) with Python's 'osgeo.gdal.Polygonize'; 3. Voronoi cells for the vectorised graphical units. Voronoi cells are synonymous with Thiessen polygons and equivalent to the mathematical morphological operator SKeleton by Influence Zone (SKIZ). Any location inside the Voronoi cell is closer to its graphical unit than any of the other sample points. The dual graph of a Voronoi diagram is a Delaunay triangulation for the same set of nodes; 4. Result of the geometric graph recording with labels showing the types of nodes; those which share a limit of their Voronoi cells will also share an edge in the geometrical graph (red nodes: graphical units, grey nodes: morphological units).

nodes is written in a text file (.csv). For each decoration a single shapefile for nodes and a single text file for edges are created. Programming offers the possibility to mix GIS, graph theory and database in a single interface. We used Python (v. 2.7), a multi-paradigm language, with its numerous libraries (Figure 5).

A characteristic of graph theory is that, unless otherwise specified, the only important thing is how nodes are connected. As a result, there is no rule for their representation (Mathis, 2003). This allows us to register drawings realised in different manners: front view, top view, unfolded view, etc.(see Figure 4). For the spatialized units, and the definition of their relationship, we assume that two or more units share an edge (i.e. are connected) when there is no other unit between them. In other words, a link exists when their Voronoi cells are contiguous. This can be represented as a partition of the whole space of the decoration (Figure 6).

Type of Units

Ceramics can be considered as a set of morphological features (type of rim, neck, shoulder, etc.), plastic features (like handles) and graphical features. Therefore, to record and analyse ceramic decorations, we distinguish three types of Units (U): Morphological Units (UM), Plastic Units (UP) and Graphical Units (UG). These units (UM, UP, UG) are the most basic and only elements needed for the study of ceramic decoration. The decoration could therefore be considered as a 3-mode graph. Typology of the units is recorded in a single text file (.csv) where each line records a predecessor and one of its successors. This hierarchical structure is a particular case of a directed graph; it is a tree where units share an edge with only one predecessor. For example, these three lines: 'U;UM' and 'U;UP' and 'U;UG' are interpreted as: 'types UM, UP and UG are subtypes of U' or 'UM, UP and UG inherit from U' (Figure 7).

As said, each successor inherited from its predecessors. This allows a dynamical and recursive definition of each unit. For example, a 'horse' is defined as Figure 8.

This hierarchical structure permits comparison between ceramics with different kinds of resolution by a process of generalisation (by going up the tree) or specification (by going down the tree). The typology of units can easily be changed, by a simple editing of the text file, and employed for other bodies of material.

Morphological Units (UM)

We define the UM as continuous parts of the ceramic support. A given type of UM is only represented once

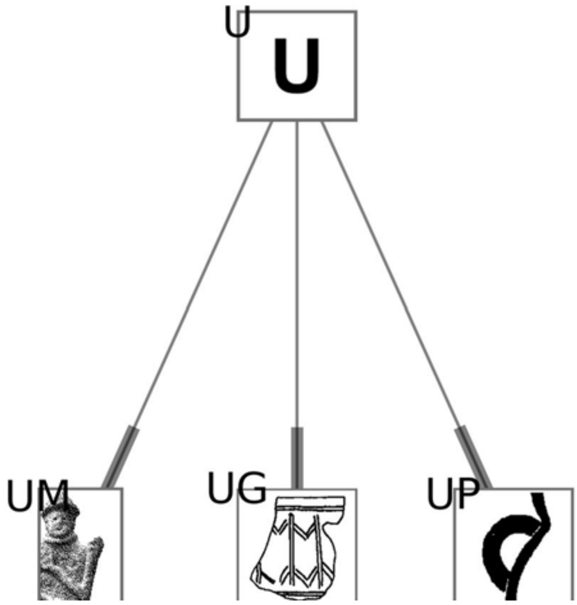

Figure 7. The upper part of the hierarchical typology (top of the tree) showing the three types of units used in the decomposition of decorations. The graph is handled with the library 'networkx', images with 'Image' and the spatialisation library is 'pygraphviz'.

on a ceramic. For example, there is only one 'neck', one 'base of neck', etc. (Figure 9).

Two particular UM need to be commented: 'high' and 'NA'. Ceramics are mostly surfaces of revolution rotated around the *z*-axis, meaning that most distinctive information of the ceramic surface will refer to the *z*-axis. The 'high' unit is useful when the rim is missing but the shard can be oriented; an identical solution would have to declare a 'down' unit. The 'high' unit allows us to recognise the top of the ceramic and gives information about the location of graphical units on the ceramic surface. The 'NA' unit (i.e. *No Data*) informs us about the entirety of the ceramic. When a ceramic has a 'NA' value, it is incomplete. The 'NA' unit permits us to control the 'edge effect' which appears for features placed near the border of the region of interest (ROI); information on their neighbourhood is partly missing.

Plastic Units (UP)

Distinction between UM and UP is not necessarily evident. For example, carination could be considered as a plastic unit (UP) while handle could be considered as a UM. Therefore, the distinction between UM and UP is made according to whether it is possible to have more than one of these units on the ceramic. If so, units will be considered as UP (for example, 'handle' and 'hole'). Similarly, 'groove' could be considered as UG (Figure 10).

Graphical Units (UG)

As noted, UG's decorations are the most complex to individualise and record. The registration grid for the UG attributes present here is a balance between an explicit but long coding and a short coding with different rules of transformation (like translation, rotation and homothety). In most cases, we choose the second solution with a minimum of UG types, and a minimum of variables. We created one field for the UG typology (*Type*), one for its rotation (*Orientation*), one for its homothety (*Auto*), two for its translation in column and/or in line (*Nb_col*, *Nb_lin*), and three to record the missing data of its homothety (*Incomp_Auto*), of its translation: in column (*Incomp_Col*) and in line (*Incomp_Lin*). These latter fields are set to 1 when part of the graphic information is lacking.

Description of the UG's variables

Two contiguous UG are said to be different when they have, at least, a different value in one of these fields: *Type*, *Orientation*, and *Auto*.

Type

Graphical units (UG) are divided into two main categories: geometrical, the most common (Figure 11), and figurative (Figure 12).

```
1    definition={ U:"unit",
2                 UG:"graphical 'U'",
3                 figurative:"figurative 'UG' ",
4                 zoomorphic:"'figurative' representing an animal",
5                 quadruped:"'zoomorphic' with 4 legs",
6                 horse:"'quadruped' having a horse shape"}
```

Figure 8. Example of a 'horse' definition ('horse' sub-graph) in a Python dictionary called definition. A dictionary is composed by keys (left of the colons) and values (right of the colons). The definition dictionary is browsed and the text present in simple quotes (for example, 'U' at line 2) in the field value is recognised with Python's regular expression library ('re') and replaced by the value which has the same key. For example, the developed expression of horse is a 'graphical unit figurative representing an animal with 4 legs having a horse shape'.

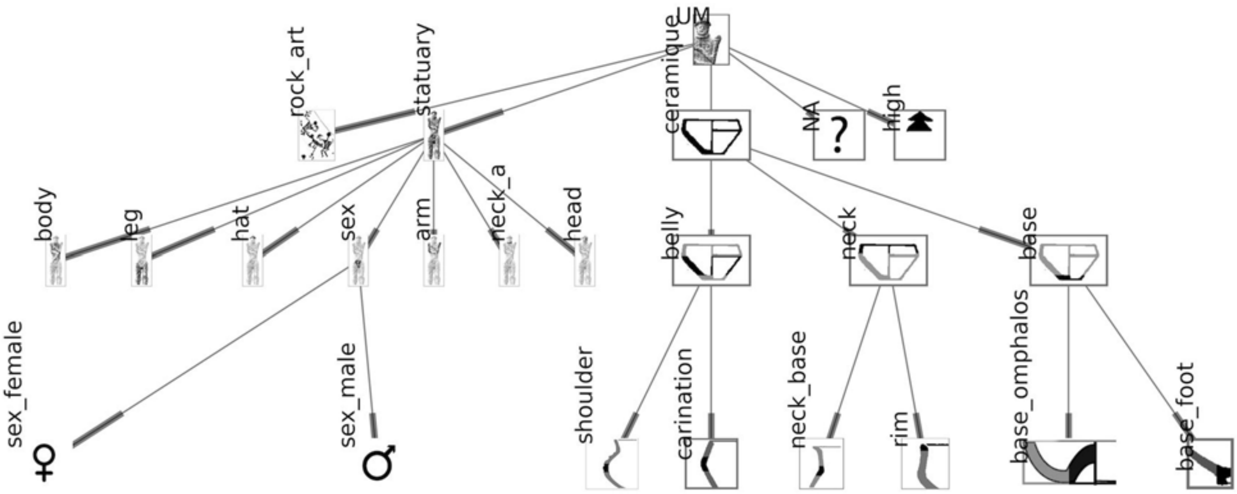

Figure 9. The UM subgraph. Each element is a specification of its predecessors. Here, for example, 'rim' and 'base_of_neck' are specifications of 'neck' because the 'rim' and the 'base_of_the _neck' belong to the morphological unit 'neck'.

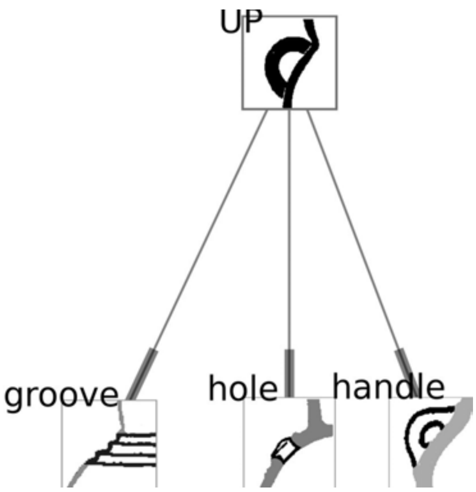

Figure 10. The UP subgraph.

At the same level in the typology tree (i.e. family intra-variability), distances between UG are calculated taking into account presence/absence of attributes (for 'anthropomorphs': position of arms, head, etc.), addition of colours, technique (adjunction, impression, etc.), etc., using Factorial Analysis (FA) or MultiDimensional Scaling (MDS). With the 'figurative' and 'geometrical' subgraphs, a third one, called 'other', has been created to record particular cases: 'vacuum' (empty), 'undeterm' (undetermined, unsolvable), 'to_determ' (undetermined, potentially solvable). A 'vacuum' is recorded between two or more UG when there is a surface that remains empty despite a sufficient area to draw one of the contiguous UG; 'undeterm' and 'to_determ' are useful for the (probable) corrections.

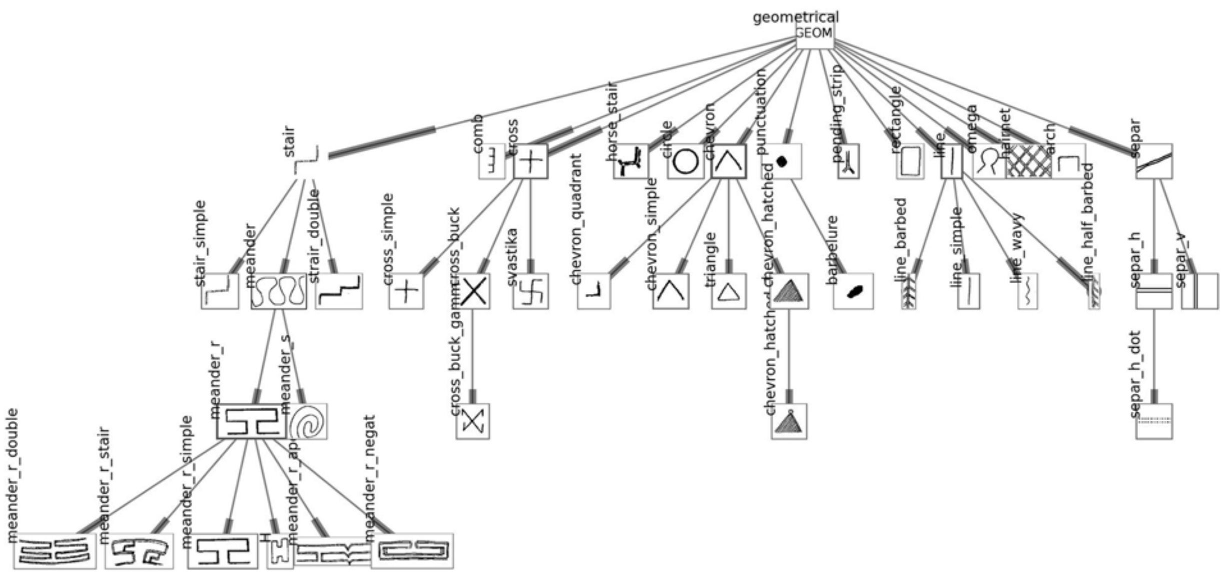

Figure 11. The 'geometrical' subgraph (subgraph of UG).

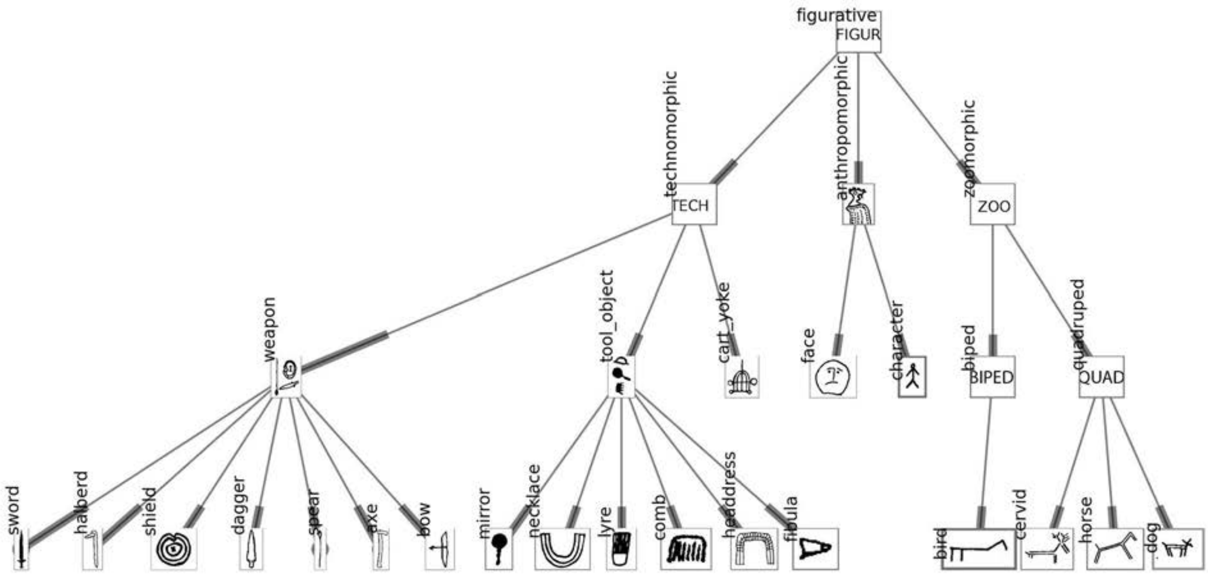

Figure 12. The 'figurative' subgraph (subgraph of UG).

Orientation

Synonym: rotation.

The default orientation of a graphical unit is given in the typology tree. Each quarter of rotation (clock rotation) is indexed by a different integer from 0 (default orientation) to 3 (oriented to the left) passing through 1 (turn to the right) and 2 (turn downwards).

Auto

Synonyms: homothety, change of scale, nested.

When a figure is repeated with amplification/ reduction, and a low translation, the number of these amplifications/reductions is recorded in the field *Auto*.

Matrix variables (nb_col × nb_lin)

Synonyms: repetition by translation.

Two columns record the translation process: *Nb_col, Nb_lin*. When an UG is repeated various times, in column or in line, the number of repetitions is recorded in a matrix. By default a single UG has a 1 × 1 matrix.

Equivalent cases

When geometrical graphical units are contiguous, figure determination can be ambiguous (Van Berg, 1994), and therefore there can be several ways to register them (Figure 13). For those cases, when two or more coding could define the same figures, classes of

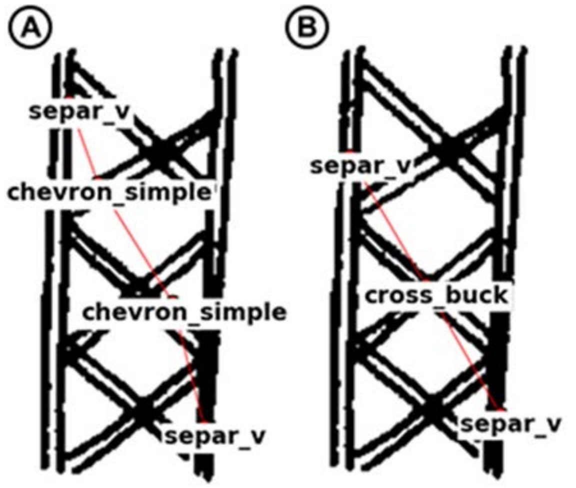

Figure 13. Two ways (A and B) to code differently the same pattern of UG. A: two columns of three 'chevron_simple', the first turned to the left, the second turned to the right; B: a column of three 'cross_buck'.

equivalence are recorded in the Python script and read during the graph analysis (Figure 14).

Study of composition

As already noted, combinations (patterns, figures, etc.) and locations (near the rim, above the carination, etc.) of units are not recorded with a priori qualitative categories, but recovered after the analysis of the spatialized graph. There is no need to present all possible cases. Graph theory makes descriptions and categorisations unequivocal.

As an example, for the corpus of Mailhac I ceramics, scholars have recognised iconographic differences (graphical units and organisation of these units) between the decoration schemes of eastern and the western Languedoc (Carozza, 2000; Janin, 2009). The iconographic register of eastern Languedoc is particularly rich (‘*le registre iconographique est particulièrement riche*’, Carozza, 2000, p. 11). To quantify precisely this ‘richness’, multivariate analyses performed on the ‘vocabulary’ (presence/absence, numbers or types of graphical units) and network indexes calculated on ‘syntax’ (spatial/topological organisation of these units) will permit us to measure and compare ceramic decorations at the graph scale (Figure 15) or at the local scale (Figure 16).

As an example, to identify which UG are located above the ‘shoulder’ (a UM) on a decorated ceramic (Le Moulin’s tomb 142, here Figure 16), the following query is pasted to the application (Figure 17).

Conclusion

Ceramic decorations, as the most common elements of the symbolic subsystem (Renfrew and Bahn, 1991), have often been considered as privileged elements to the identification of cultural facies (definition of ‘style’).

```
A  B
1  caseA_is_in_graph=False
2  caseB_is_in_graph=False
3  caseA=[('separ_v',0),('chevron_simple',1),('chevron_simple',3),('separ_v',0)]
4  caseB=[('separ_v',0),('cross_buck',0),('separ_v',0)]
5  # case A
6  for typo_caseA, orientation_caseA in caseA:
7      for n in graph:
8          type_node=n['type']
9          orient_node=n['sens']
10         if typo_caseA == type_node and orientation_caseA == orient_node:
11             ct=ct+1
12             if ct == len(caseA):
13                 caseA_is_in_graph=True
14                 break
15         else:
16             ct=0
17 ct=0
18 # case B
19 for typo_caseB, orientation_caseB in caseB:
20     for n in graph:
21         type_node=n['type']
22         orient_node=n['sens']
23         if typo_caseB == type_node and orientation_caseB == orient_node:
24             flag=1
25             ct=ct+1
26             if ct == len(caseB):
27                 caseB_is_in_graph=True
28                 break
29         else:
30             flag=0
31             ct=0
32 # verification
33 if (caseA_is_in_graph and caseB_is_in_graph) == True:
34     print "Same pattern (group of UG) have been coded differently in the graph"
```

Figure 14. Pseudo-Python code to recognise if the same pattern of UG has been coded differently for a given graph (see Figure 13 cases A and B). Firstly, we suppose that case A and case B do not exist in the graph (lines 1 and 2). Case A is declared as a Python list of tuples where the first variable of the tuple is the type and the second its orientation (lines 3 and 4). Both cases are researched in the graph by iteration on the nodes of the graph and lists of case A and B (lines 6 to 16 for case A and lines 19 to 31 for case B). When the same sequence is identified in the list and in the graph, the counter (ct) become equal to the length of the list and the value of the case is turned to True (lines 13 and 27). When case A and case B are both True, it means that the same pattern (group of UG) has been coded differently in the graph (line 34).

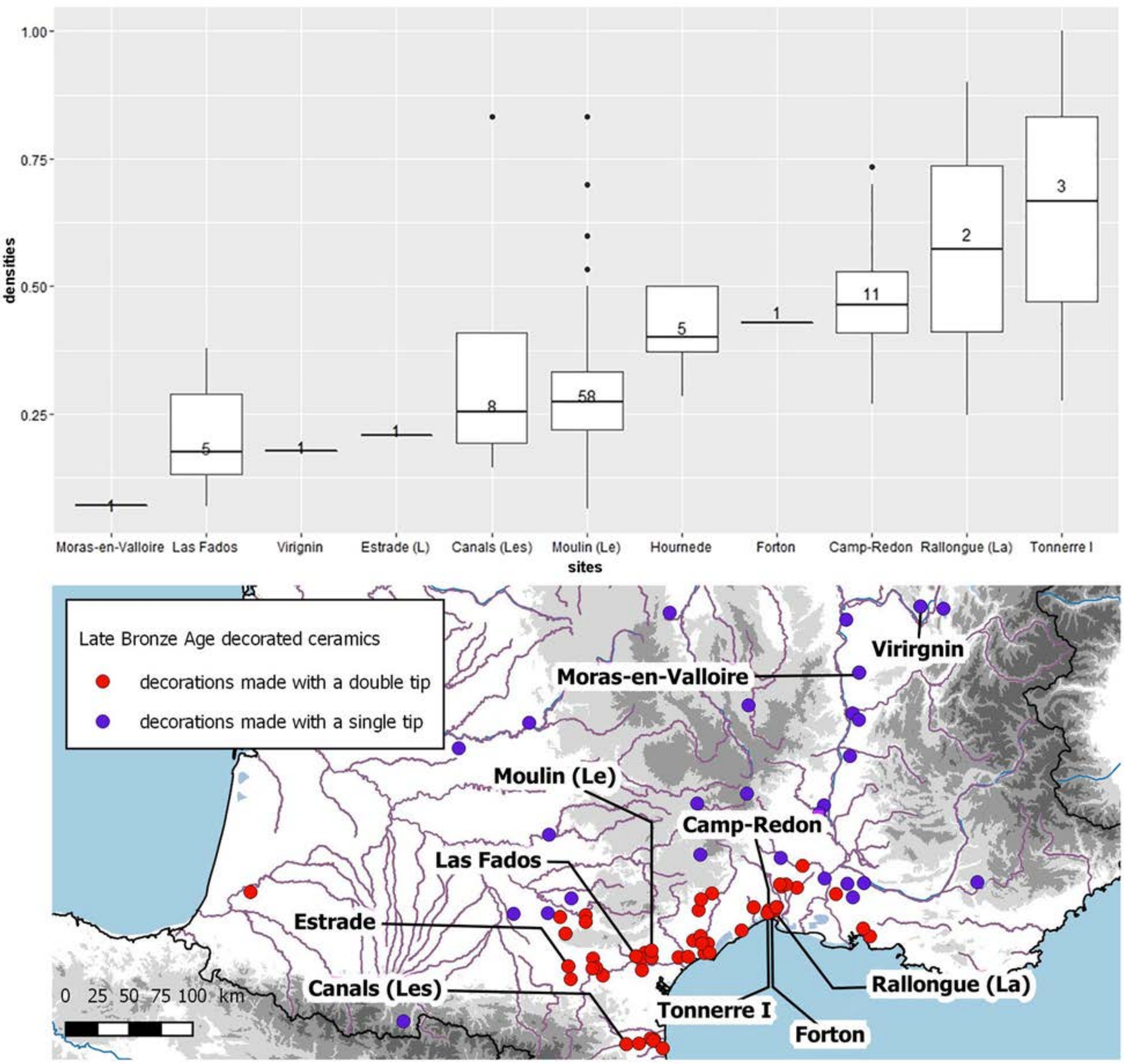

Figure 15. Boxplots of decoration densities for Mailhac I ceramics and locations of sites.

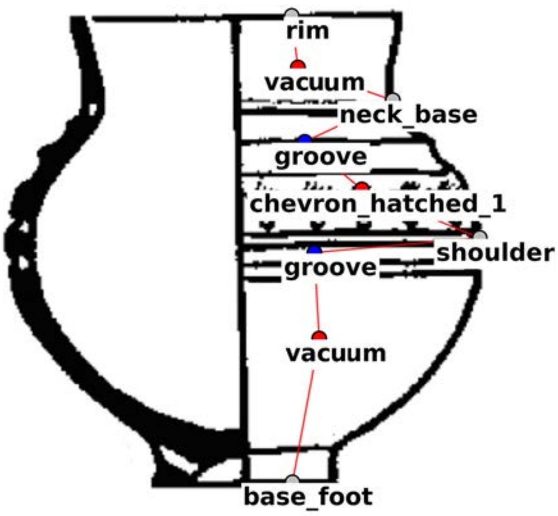

Figure 16. Geometric graph for the decorated ceramic from tomb 142, Le Moulin necropolis (Late Bronze Age). The 'chevron_hashed_1' frieze (1 × 20 by extrapolation from the drawing information) is located on the upper part of the ceramic; this means — in graph theory — that the frieze is in the topological subgraph of the 'rim'.

```
1 for n in graph:
2     if n['type']== 'shoulder':
3         g.remove_node(n)
4 for sub_g in nx.connected_component_subgraphs(g):
5     for node in sub_g:
6         if node['type']=='rim':
7             for sub_node in sub_g:
8                 sub_g(sub_node['up_the_shoulder'])=True
```

Figure 17. Pseudo-Python code to recognise which UG are above the 'shoulder' of the ceramic. The graph g is divided into different connected components after the node 'shoulder' is removed (lines 1 to 3); as noted, it could only have one shoulder (a UM) by decoration. Each connected component is browsed (line 4). When a UG is recognised as the 'rim' or a 'high' in the component (line 6), the field 'up_the_shoulder' of the UG of the component is updated to True (line 8).

In Pre- and Proto-historic contexts particularly, only signifiers are conserved on the archaeological artefacts and the signified can only been supposed. Therefore, the first steps of iconography analyses have to be based on an analysis of the signifiers, considered as spatial sets of features, and should be closer to geometry than linguistics.

The CAA2016 session entitled 'Networking the past: Towards best practice in archaeological network science' has shown that graph theory, as a simple formal system, can be employed in numerous cases, but not always with particular relevance. For iconography and at the scale of the decoration's support, the interest of graph theory is to model the relationships (qualitative) when measures (spatial, quantitative) are difficult to calculate, mostly because of the contiguity of graphical units. More so, quantitative information (distances, azimuths, etc.) can be calculated within a GIS (spatialized networks) and recorded in the network (valued graph). The methodology briefly presented here opens possibilities of studying graphical systems with normalized indexes over a long period of time, on heterogeneous source data.

Acknowledgements

This project is supported by LabEx ARCHIMEDE from "Investissement d'Avenir" program ANR-11-LABX-0032-01. The author also wishes to thank Craig Alexander for help with English and constructive comments.

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Mieko Matsumoto and Espen Uleberg (eds) 2018. *CAA2016: Oceans of Data*
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
Oxford: Archaeopress

Vertical Aspects of Stone Age Distribution in South–East Norway

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Abstract
The online Norwegian archaeological museum database gives a unique opportunity to study large amounts of archaeological material at varying temporal and spatial scales. In this paper, the material in the collection of the Museum of Cultural History, University of Oslo, is used to visualize vertical aspects of the spatial and temporal find distribution in the counties Oslo, Akershus, and Buskerud. The analysis will combine two material groups at different temporal scales to reflect possible changes in the Stone Age landscape use (11000–2000 BP).
Using Exploratory Data Analyses (EDA), a resulting visualization will relate the archaeological sites to the Stone Age forest-limit. The finer time intervals Middle Neolithic B and Late Neolithic (LN) reflect the gradual expansion towards the inland areas in the LN. Visualization at finer temporal and geographical scales will contribute to the current debate about the shift to extensive pastoralism at the beginning of LN in South–East Norway.

Keywords: MUSIT database, MSUP/MTUP, EDA, Norwegian Stone Age, visualization

Introduction

The online Norwegian archaeological museum database, MUSIT (MUSeum IT) database, gives a unique opportunity to study large amounts of archaeological material from a whole country at varying temporal and spatial scales. This article will use the material in the collection of the Museum of Cultural History, University of Oslo, to visualize vertical aspects of the spatial and temporal find distribution in the counties Oslo, Akershus, and Buskerud (Figure 1). The analysis will combine two material groups at different temporal scales to reflect possible changes in the Stone Age landscape use (11000–2000 BP). One is material found on sites, and the other is single artefacts that could be ascribed a symbolic value.

The geographical area of the three counties reaches from the inner Oslo fjord in the East to the mountain regions in the West. The landscape rises gradually, up and above the forest-limit which today is at around 1000 m a.s.l. The paper will discuss the impact temporal scales can have on the understanding of distribution patterns and the representability of the two artefact groups in the higher altitude regions.

Figure 1. South Norway and the three counties Oslo, Akershus, and Buskerud. The red line indicates the height profile shown in Figure 3.

The databases

The Norwegian university museums have been cooperating to create common database systems for nearly three decades. The database model for archaeology and ethnography is event based, and builds on the CIDOC-CRM (Conceptual Reference Model), which is published as ISO 21127:2006.[1] The work started in the 1980s, and the database is now maintained and developed by the cooperative initiative MUSIT, created by the university museums in Oslo, Bergen, Stavanger, Bergen, Trondheim, and Tromsø (Uleberg and Matsumoto, 2009; Matsumoto and Uleberg, 2015b). The database system consists of separate instances for collections in cultural history (archaeology, numismatics, ethnography) and natural history. Further development started in 2016 to join the instances and create one basic structure for all. The new system will be more modular and scalable, and will make it possible to combine information in new ways. Artefacts, persons, and places will be linked to events like surveying, excavation, conservation, and cataloguing. In this way all relevant information connected to each event can be retrieved.

The original museum catalogues have been converted to the MUSIT database system. The Norwegian university museums have published their annual acquisitions since 1866. The online publishing continues this tradition as the catalogues are created in the MUSIT database. Metadata for the archaeological artefacts are available online at http://unimus.no/ together with ethnographic and numismatic collections. The metadata can include a site ID linking to the national Sites and Monuments Register (SMR), *Askeladden,* with a site description and survey history. The number of published database entries from the archaeological collections has passed one million. In addition to the export option from queries on the web page, it is free for anyone to download the complete data set and use it for visualization and analysis.

Stone Age in South–East Norway

The project Dynamic Distributions (Matsumoto and Uleberg, 2015a; Uleberg and Matsumoto, 2015, 2016) concentrated on Stone Age artefacts like axes, sickles, and daggers, especially from the Neolithic period, to visualize distribution patterns related to landscape types. This material was mainly single finds without context. The present paper will expand on this material and include both smaller sites discovered by chance or through planned surveys, and large excavated sites. Artefact types and sites can be used for a range of analyses depending on their spatial and temporal context. Some of the sites can be dated rather precisely through find typology, within a time span of a few hundred years. The isostatic land rise after the Ice Age makes it possible to date coastal sites with a similar precision. Radiocarbon dated sites can also be placed within a narrower time frame than others. A large part of the material is from small sites that are difficult to date with higher precision.

The small sites can consist of very few pieces of worked stone. Apart from the coastal areas, where one might find ice transported flint, there are no natural sources of flint in Norway. All flint found inland must therefore have been brought there by human agencies, and even one or two pieces of flint debris can be interpreted as indications of some kind of human activity. The national surveys in the 1960s defined a site with more than three pieces of debitage as an occupational site of unknown duration and function (cf. Glørstad, 2006, p. 71).

The georeferenced finds from the MUSIT database give an opportunity to look at how various landscape types were used during the Stone Age. Each site is a place where one or several events took place. It can be claimed that a small site, a site with only a few or few distinct types of artefacts, is a place that was used for a special activity and over a short time span. Large sites with a more diverse inventory are traces of more people conducting a wider range of activities over longer time. A small site could indicate a short stop for mending tools or butchering, while the larger site could be produced by recurring events at the annual summer camp of a group of hunters (Binford, 1979, 1980; Uleberg, 2008). The pattern described by the sites could reveal a set of taskscapes (Ingold, 1993) inhabited by Mesolithic hunter/gatherers and Neolithic pastoralists.

The oldest sites in Norway are coastal sites dated to around 11000 BP, based on the height level and the isostatic rebound after the Ice Age (Jaksland, 2014, pp. 16–22). The earliest sites in the high mountains are dated to around 7000 years BC (Indrelid, 2009, p. 63). This indicates that humans were present at the coast in Norway at the end of the last Ice Age, and in the mountain areas soon after the vegetation could give living conditions for animals that could be hunted. Sites in the mountains cover the whole Stone Age, but the annual movement cycles including the mountain areas have varied. Continuity in economy and subsistence pattern has been a traditional way of looking at the Stone Age in the mountain areas. On the contrary, sites dated by typology and ^{14}C have indicated a discontinuity, and this hiatus has been explained by a climate change that led to a deterioration of the reindeer population and consequently less human activity in the mountains (Moe *et al*., 1978). As more ^{14}C dates have become available, it is possible to discern unique hiatuses in separate mountain and woodland regions. This could imply that the reason for each hiatus cannot only be found in general climate changes, but in other variables like social organisation (Boaz, 1998; Indrelid, 2009, p. 64).

[1] http://www.cidoc-crm.org/

The archaeological material

The material included in this presentation can broadly be separated in two categories. One is the large stone artefacts like axes, sickles, and daggers, and the other is debitage and expedient or informal tools. The biography of the artefacts in these two groups, both in prehistory and in recent history, can be very different. Prestigious tools like the Early Neolithic flint axes and the carefully made Late Neolithic flint daggers have probably had a special meaning assigned to them. They will more often occur in graves or depots and are rarely found at occupational sites. The places they were deposited seem to have been carefully chosen, and were places with meaning assigned to them. It is probable that most of them have been deliberately placed in graves or as offerings. These artefacts are recognised as beautiful objects even to us. They are therefore often noticed and reported to a museum when they are found. The find context is often not very detailed, but on a larger scale they add to the knowledge of Stone Age landscape use. Visualizations of this material have been published earlier (Matsumoto and Uleberg, 2015a; Uleberg and Matsumoto, 2015, 2016).

The other category of archaeological material is working tools, expedient tools, and debitage from tool making which are left where they were produced and used. They are from a series of events that reflect usages of the landscape. The site was chosen on basis of what was a good place to settle or at least to stop and perform one or more tasks (Uleberg, 2003). Close to quarries there can be a series of small sites connected to procurement of raw materials. Long series of events have taken place at lakes in the high mountains. Events can have been recurring at the same site, making it a cumulative palimpsest (Bailey, 2007) of various events close or far apart in time. Other events can have happened in close proximity, but far enough away to be noted as a separate site. In many of these cases it would be more correct to describe such groups of sites as large activity areas, and try to document them through the conception of a site-less survey (Dunnell *et al.*, 1983). Such problems are difficult to register in the object database as it is today where each site shall have one entry and a point coordinate. The distribution of these types of sites in the landscape will tell us more about procurement strategies and subsistence patterns.

The two groups of material have distinctly different proveniences. Prestige artefacts like axes, sickles, and daggers in flint are often found by agricultural or construction work. The exact location of the site is not always recorded. Other material derives mainly from excavations and planned surveys for modern development projects. Most of the sites in the mountain regions are found around lakes and rivers due to the surveys that were done in relation to construction work for hydro-electrical power. In areas closer to the coast, discovery of sites follows road and railway lines. In a few areas there are a high number of known sites due to surveys conducted by individuals interested in their local prehistory, but these are exceptions. These artefact biographies must be taken into account when the distribution patterns are interpreted.

The concentration of prestige artefacts to agricultural areas could be a result of modern agriculture more than an actual prehistoric distribution pattern, but this is not supported by recent studies (Hagen, 1944; Glørstad, 2002; Amundsen, 2011). The fact that these artefacts are rarely found with other artefacts at excavations and surveys gives credit to the idea that their distribution pattern is the result of changing ways of looking at the prehistoric landscape.

Spatial and temporal precision

Single finds and sites are with varying precision attributed to places in time and space. In the database this is represented by a single coordinate and a general dating. This point in time and space is an abstraction from the event that had a duration and an extent which can now only be deduced through the remaining objects. Finds from more recent excavations and surveys can have a very high spatial precision level. Finds recovered by chance will in general have a lower spatial precision level. This spatial precision level can be crucial when deciding to include a specific find in a visualization. A high precision level is necessary when analysing proximity to water and even more when studying the relative position of finds within a site. Large area distribution visualizations can include finds with much lower precision levels. An example could be the distribution of slate artefacts in Norway which are rarely found in the South but quite common in the North. At such a coarse scale even a point within a parish could be included. The parish coordinate can be sufficiently precise at one scale level but totally misleading at another. Visualizations at different spatial scale levels can include artefacts with varying spatial precision levels. In this process, the material will be grouped according to the areal units used in the database, *e.g.* sites, cadastral units or landscape zones. The selected area units and how they are calculated can have a great impact on the results, and eventually give spurious patterns. This is known by geographers as the Modifiable Areal Unit Problem (MAUP) (Harris, 2006, pp. 48–50; Dark and Bram, 2007).

The visualization is spatiotemporal. The temporal precision can be seen as an analogue to the spatial precision. Examples of archaeological time units can be the Early, Middle, and Late Neolithic, centuries or millennia. Some artefacts, and to some extent ^{14}C

dates, have a relative high temporal precision level. One example from the Norwegian Stone Age is the axes from Middle Neolithic B (MNB). MNB is a short interval (2700–2400 BC) where the axes are typologically distinct, and exist in a quite high number. The other extreme is expedient tools or tool making debris from small sites without any diagnostic datable material.

The date for such a site with only debitage and one or more artefacts will be a main archaeological period, like 'Middle Neolithic' or 'Stone Age'. A narrower time span like 'MNB' can be annotated for typologically well-defined artefacts. The precision of the dating is implicitly given by the length of the period. MNB is a relatively precise dating with a short time span (ca 300 years), while 'Stone Age' is far less precise (9000 years).

An archaeological temporal scale can be both the structure of the archaeological deposit and the scale of measurement and interpretation. In an archaeological data set there can be relatively few observations during a given period, and consequently patterns of landscape use can be perceptible only if the time scale is large enough for a certain pattern to emerge. The scale of explanation must therefore relate to the scale of observation (Holdaway and Wandsnider, 2006). Most of the Stone Age sites included here are dated typologically, and the scale of observation is determined by the accuracy of the artefact typology.

The space/time slices used in the analyses must be chosen according to how well the artefacts and sites can be dated, but also in a way that provides enough material to let recognisable patterns emerge. For the purpose of visualizing the temporality of the sites, historicity, and changes over time, it is necessary to group the material in temporal entities. The temporal entities will also have a strong impact on the analyses, and in analogue with MAUP, this can be referred to as the Modifiable Temporal Unit Problem (MTUP). MTUP consists of points in time, duration, and temporal resolution (Çöltekin *et al.*, 2011).

The time-space data set is aggregated and segmented into groups to illustrate the vertical aspects of the site distribution during the Stone Age. Schematic time-space positions are illustrated in Figure 2. Single artefacts are found at a point in space, and the time interval will depend on whether or not it is a typologically well-defined object from a shorter archaeological period. The events at an archaeological site may have occurred over shorter or longer time-spans and within one or several archaeological periods. The sites are formed with cumulative palimpsests. Typologically dateable artefacts from the same site could be from one or several close or far distant archaeological periods, and the debitage could be from

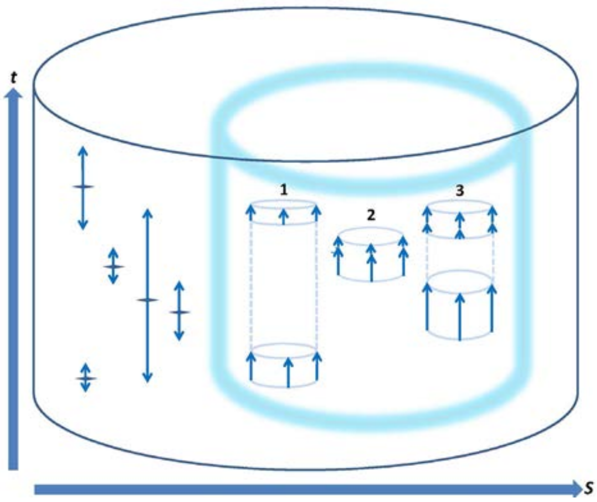

Figure 2. Schematic presentation of time (*t*)-space (*S*) temporality of a single find (double arrow with horizontal line) and the sites (1–3) with expanded spatial area. Type 1 is a place which was used in two separate far distant periods, while type 3 is a combination of distant and consecutive periods. Type 2 shows only consecutive periods.

the same or even from totally different periods and events. Comparing the spatiotemporal distribution of material from several sites can give new understanding of the time perspectives (Bailey, 2007).

The spatial precision levels are included in the metadata in the database. The precision levels are qualitative and not quantitative. A quantitative precision level will in many cases be given as a point or line with a measure of inaccuracy. For the archaeological finds this would not reflect the actual provenience information. The highest site precision level in the MUSIT database is the exact artefact location, followed by the site location. The other categories include cadastral units, ecclesiastical and civil administrative units. It also includes place name categories like island, lake, mountain, and so on, as used by the Norwegian National Mapping Authorities (*Kartverket*, www. kartverket.no). The area of a cadastral unit can change over time, and it is hardly possible to know the extent of the unit when a certain artefact was found. The exact area that is meant by a certain place name can also be debatable. For these reasons, it would not be possible to describe the precision level quantitatively, and the levels used in the database are defined as qualitative.

Each entry in the database is the concrete remains of a series of events. The event in prehistory produced one or more artefacts. These events were of longer or shorter duration, and the recovered archaeological material is the accumulation of these events. The modern events that decide our impression of the prehistoric reality include accidental discovery, surveying, excavation,

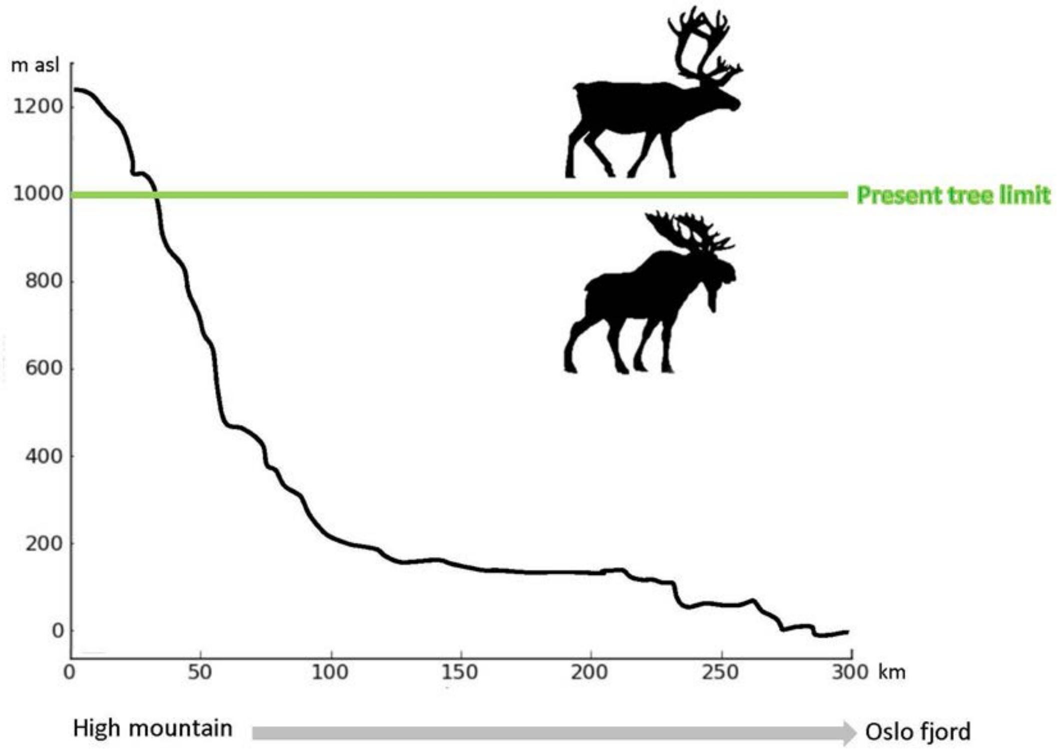

Figure 3. The height profile from the Oslo region to the high mountain area in Buskerud county. The green line indicates the present forest–limit at about 1000 m a.s.l. The main game animals are the reindeer above and the moose below the limit.

and cataloguing. Each of these events involved people and took place in a time/space continuum.

Many sites may have been visited several times. Near the coast around Oslo the combination of the eustatic land rise after the Ice Age and a preference of coastal sites on small, sheltered, flat areas determine the site distribution. Local topography creates a place very well suited for habitation as long as it is at the coast, but the qualities of a safe harbour are lost when the eustatic rise has made it an inland site. Assuming that they are coastal sites, they can be dated based on the land rise curve. Other sites in this area will today be farmland, and have a history as an early hunter-gatherer coastal site and a Late Neolithic (LN) agricultural inland site.

Identifiable stratification with cultural layers is very rare on Stone Age sites in East and South Norway. Especially at the sites in the high mountains, the majority of sites are exposed or just below a thin layer of turf. Artefacts from different periods can therefore be found in the same layer. The use of stone tools has continued through the Bronze Age and the Early Iron Age, and as long as a site has only a few pieces of stone it is hardly possible to specify the dating of the activity. Because of this, the term Late Stone Using Period (2000–0 BC) has been used for artefacts that could be from the chronological Stone Age but also from the Bronze or even Early Iron Age (Indrelid, 2009, p. 11). The term Stone Age will in this paper include the Late Stone Using Period.

The paleoenvironment

The forest-limit is a major environmental factor in the mountains, and the present situation is the result of climatic changes and long lasting human impact. The modern combination of less grazing and higher temperatures result in regrowth of trees at higher altitudes, and the present forest-limit in Buskerud county has passed 1000 m a.s.l. (Dvorak, 2013) (Figure 3). The Stone Age sites in the mountain areas of Buskerud county are still above the forest-limit. To understand the ecological and social space and how it changes when moving towards higher altitudes, it is necessary to establish the forest-limit during the Stone Age, and whether the sites at higher altitudes were in a totally different environment or in a peripheral continuation of the lower altitude forest (Uleberg and Pedersen, 2013).

The Holocene climate history of South Norway can be divided into three successive parts. The first phase is characterised by an early climate maximum with rather high temperatures, the melting of the last glaciers and plant immigrations. During the second

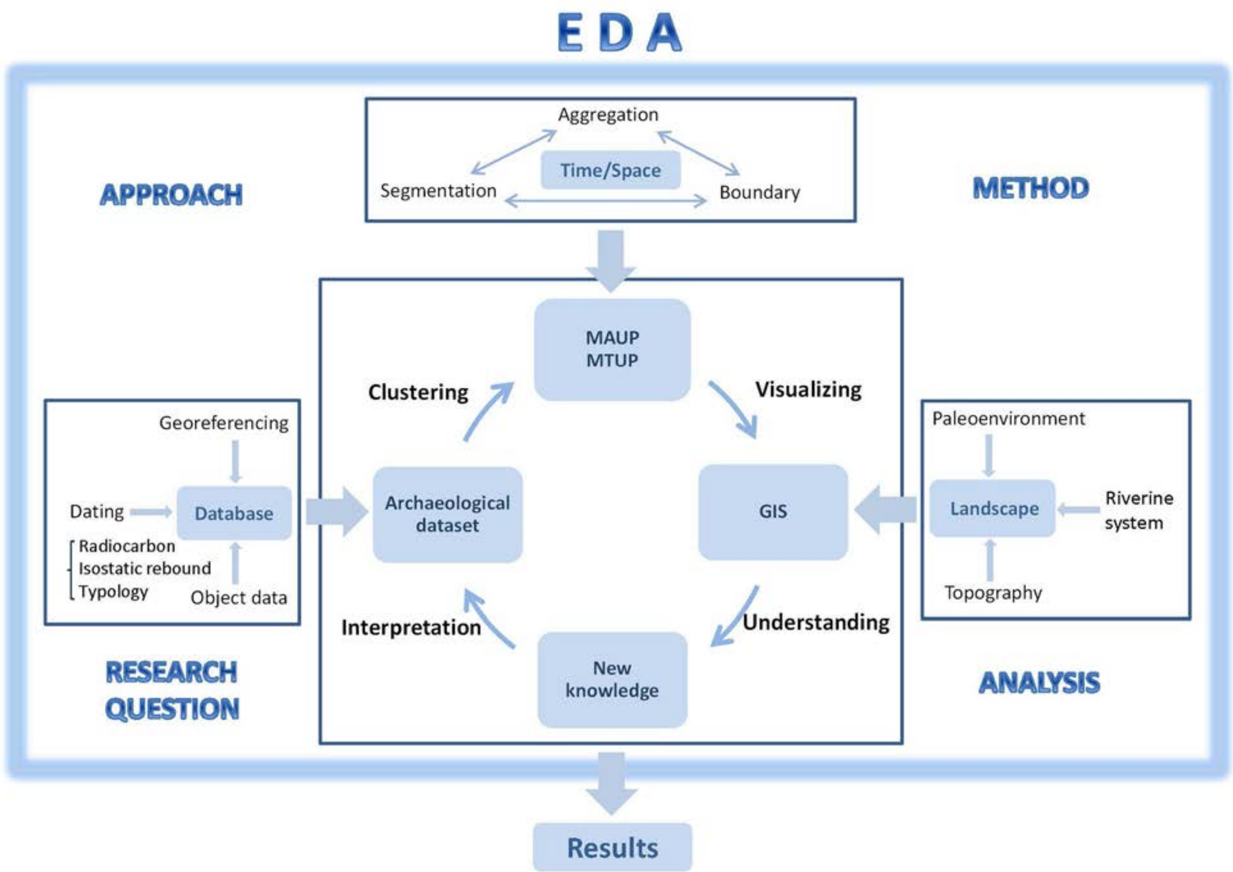

Figure 4. Exploratory Data Analyses (EDA) using the MUSIT database and landscape analyses. The schema illustrates how different ideas of approach, method, and analysis relate in response to the recurrent research questions in archaeology.

phase, the Holocene thermal optimum, the pine forest reached its maximum as early as around 8700–8500 BP. The forest-limit varied along an East-West-gradient, and reached 1250 m a.s.l. in the central parts of South Norway, 1200 m in the eastern parts and 1100 m a.s.l. in the western parts. The third phase is characterised by a temperature decrease and consequently a forest-limit decline (Selsing, 2010). Selsing advocates a beginning of the pine tree decrease from 6700 BP, then an expansion of birch but a further decline of the pine forest-limit from 5500 BP and an increased decline in forest-and tree-limit from 4700 BP (*ibid*., p. 89, table 11). Faarlund and Aas (1991) have based their estimations on preserved tree-trunks in the high mountains, and argue that the tree-line was rather constant from the early climate maximum until the deterioration at the beginning of the Iron Age (2500 cal BP). There is both pollen and megafossil evidence of a birch forest belt at higher altitudes than the pine during the Holocene which may have reached a maximum of 1400 m a.s.l. (*ibid*.; Aas and Faarlund, 1999). Using Exploratory Data Analyses (EDA), a resulting visualization will relate the archaeological sites to the Stone Age forest-limit.

Exploratory Data Analyses

The archaeological MUSIT database includes the descriptive object data as well as dating based on typology, ^{14}C analyses and, for the coastal sites, the isostatic rebound. An excerpt from the database relevant to the actual research question constitutes the basic archaeological data set in the analysis (Figure 4). The data set consists of georeferenced objects, dated by typology, radiocarbon analyses or isostatic rebound. The methodological approach is to order these objects in spatiotemporal clusters in a process of aggregation, segmentation, and consideration of the effect of boundaries, and in this way address problems related to modifiable areal and temporal units. The resulting clusters are visualized in GIS, where the archaeological material is related to a landscape described through topography, paleoenvironmental variables, and riverine systems. This visualization leads to better understanding and new knowledge that in turn can lead to new interpretations of the archaeological data set and eventually results that answer the initial research question.

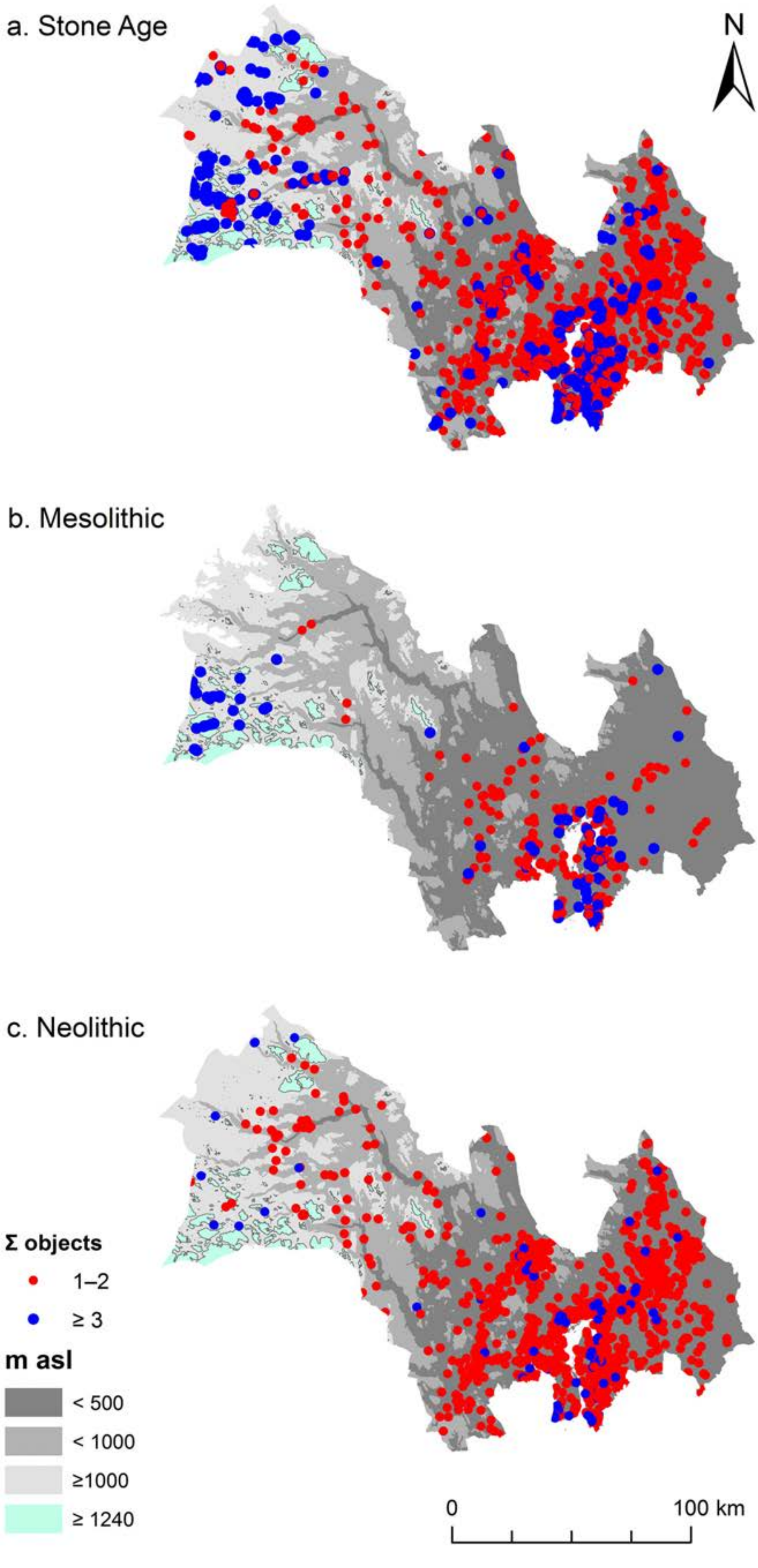

Figure 5. Long-time distribution maps for sites from the main archaeological periods in three counties; a. Stone Age (9000 years), b. Mesolithic (5500 years), and c. Neolithic (2250 years).

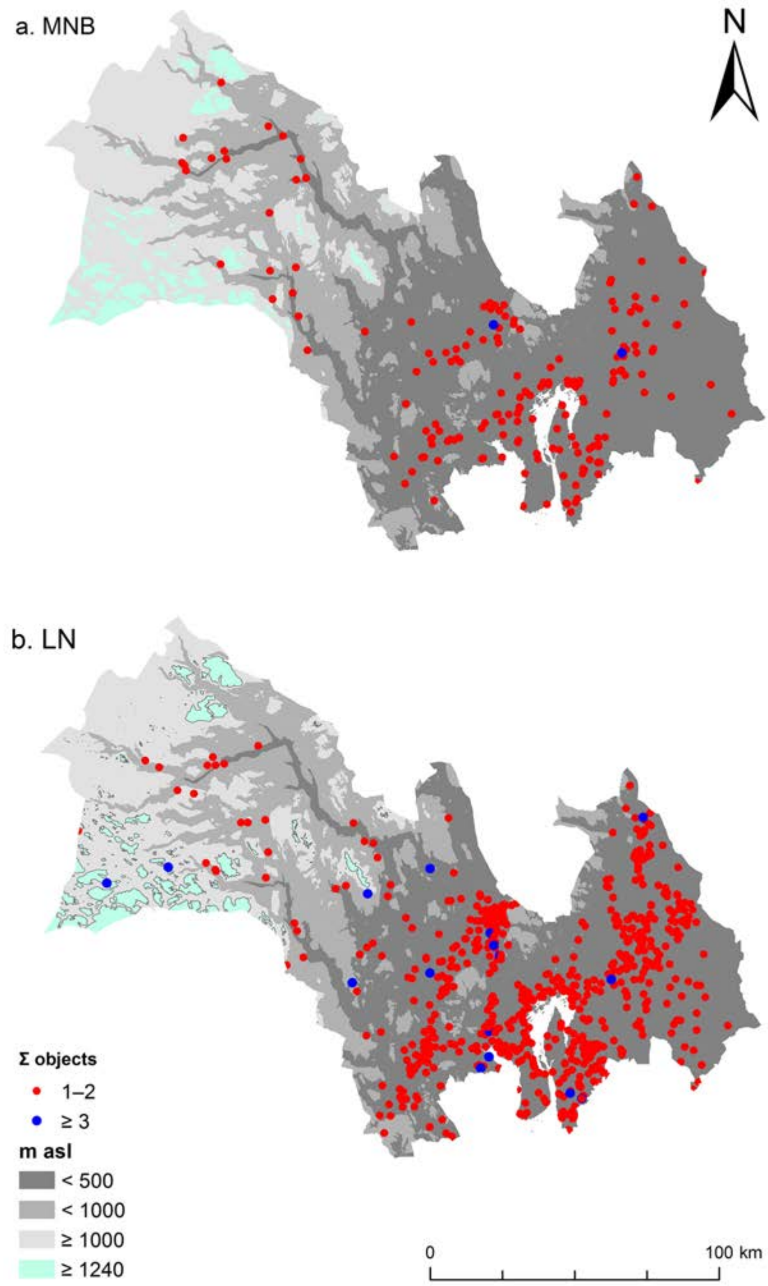

Figure 6. Distribution maps for the shorter archaeological periods in three counties;
a. Middle Neolithic B (2700–2400 BP) and b. Late Neolithic (2400–1750 BP).

Long time

The maps in Figure 5 show the distribution of sites in the three counties Oslo, Akershus, and Buskerud at different temporal resolutions. The first map (Figure 5a) shows the totality of Stone Age sites. At this scale even sites with precision levels of cadastral sites and geographical areas like lakes have been included. The main point is to visualize the vertical distribution, and therefore height levels of 500, 1000 and 1240 m is marked. The present forest-limit is 1000 m, and the contour line at 1240 m illustrates the highest forest-limit during the Stone Age.

The sites are divided in two classes: sites with one or two objects and sites with three or more. The single finds are one group, and the few sites with two objects are a separate group.

A major difference between the sites above and below 1000 m is the relative number of single finds. This is especially evident in the map presenting all Stone Age sites. The sites in the mountain areas are for the most part found by surveying around the lakes, and there are few examples of single finds. The areas at lower altitude are more populated, and many finds are made in connection with agricultural practises or construction work.

The division between stray finds and occupational sites is even clearer on the map showing the distribution of Mesolithic sites (Figure 5b). In general, there are few Mesolithic single finds, and the occupational sites cluster along the coast and in the mountain regions. Mesolithic coastal sites can be dated according to topography and height above sea level. Mesolithic inland sites are few; very few in the intermediate zone between 500 and 1000 m a.s.l. The material in the mountain sites indicates connections eastwards and the absence of sites could be due to a lack of surveying in this region.

The distribution map for Neolithic finds show a higher number of finds at the lower altitudes, and extended use of the inland regions (Figure 5c). It can however also be noted that the number of sites above 1000 m has decreased significantly. The sites are concentrated along the coast and in areas well suited for agriculture. The majority are single finds that can be included at this spatial scale, but many of them would not be included in a more detailed analysis. Artefacts of slate and grinded flint can date the sites to the Neolithic, even though a more precise dating is difficult.

The maps show that a lot of sites could only be dated generally to the Stone Age, since they are not included in the maps of Mesolithic and Neolithic sites. The Northern corner where a lake is divided by a county border is illustrative. There are several Stone Age sites but only two of them are included in the map of Neolithic sites, and the Mesolithic map has none. The Mesolithic sites at this lake would appear in the adjacent county. The area could have been expanded to include the whole lake, but then the rest of that riverine system would be missing. Spatial and temporal boundaries will to some extent always be arbitrary, and background knowledge, knowledge exceeding the area of analysis, is necessary to evaluate the results.

The maps also relate an understanding of the paleoenvironment. There are several sites at lakes above the present forest-limit, and it is possible to discuss types of hunting like reindeer versus moose/elk. The discussion of the forest-limit indicates that the strong decline in the forest-limit was as late as the start of the Iron Age, and that the Stone Age forest could grow as high as 1250 m a.s.l. On this map, there are no sites above this level, and consequently the sites have been in the forest or at least among the trees above the forest-line. This suggests that the environment has been a continuation of the forested areas and not a totally different habitat. This also supports that the absence of sites does not necessarily mean that the intermediate areas had not been inhabited: it is more likely due to surveying activity and not a prehistoric subsistence pattern.

Short time

The maps in figure 6 illustrates the distribution in two relative short time intervals, the MNB (2700–2400 BC) and the LN (2400–1750 BC). Both periods have a majority of single finds. This could be because many occupational sites are just dated as Neolithic, and therefore excluded from the analysis at this time scale. The MNB map shows activity in the form of single finds even far inland. The number of occupational sites is very low (Figure 6a). The LN map indicates inland expansion and increased activity in all areas used during the MNB. It can also be noted that LN but not MNB has sites in the mountains (Figure 6b).

A major shift during the Norwegian Stone Age is believed to have taken place at the start of the LN. There is a marked increase in the number of finds, and a subsistence shift to pastoralism. The re-occurrence of sites above 1000 m in LN can be interpreted as the result of expanding pastoralists using the good grazing grounds in the mountains during the summer season. One must however take into account that the distinctive MNB tools are axes connected to the Neolithic culture in the agricultural areas. The low number of occupational MNB sites can indicate that these sites are registered simply as Neolithic sites and the temporal precision is too low to include them in the map of certain MNB sites. LN sites are dated by axes, sickles, and daggers, and also flat flaking technique used for a tool type like points which occur more often in the high mountains.

Conclusions

The distribution of Stone Age sites at different temporal resolutions can show varying landscape use through the composition of finds at lower and higher altitudes. At the coarsest level, *i.e.* the long duration, Mesolithic and Neolithic sites are compared with the distribution of the totality of Stone Age sites. The distribution indicates that all inland sites have been in the forest, not above the forest-line, given the higher altitude of the Stone Age forest-limit. Even at this scale, it is evident that there are relatively more occupational sites at higher altitudes and more single finds at lower altitudes. This could indicate more graves and depots at lower altitudes, but could also be explained by modern surveying strategies.

The finer time intervals in Figure 6, i.e. the short duration of MNB and LN, reflect the gradual expansion towards the inland areas in LN. This phenomenon seems to be clearest at the lower altitudes. According to our earlier studies, this is a progressive and successive tendency that can be observed throughout the entire Stone Age, with gradual intensification towards LN. The study has also shown that visualization at finer temporal and geographical scales will contribute to the current debate about the shift to extensive pastoralism at the beginning of LN in Southeast Norway.

The Norwegian museum database gives good opportunities for studies at different spatial and temporal scales. Ongoing work improves the quality of existing data, and data from new excavations are added continuously. Further work can be developed towards studies on enhancement of the unique phenomena with 1) spatial extension with a comprehensive number of Stone Age finds, and 2) narrower time-sections incorporating landscape variables, riverine systems, ^{14}C dating, and more finely categorised occupational sites.

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3D and Visualisation

Mieko Matsumoto and Espen Uleberg (eds) 2018. ***CAA2016: Oceans of Data***
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
Oxford: Archaeopress

Emerging Technologies for Archaeological Heritage: Knowledge, Digital Documentation, and Communication

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Abstract
Today, knowledge of archaeological artefacts at various representation scales is required of any 3D model. The significance of constructing digital models in the domain of archaeology reinforces the theoretical bases of survey and representation, as structured systems for organising and communicating information, and for critical analysis which optimises the results obtained from the concerted work of archaeologists, architects, and informatics experts.
Presented here is a study of the Etruscan Sanctuary of Pyrgi that illustrates a complete methodology for the virtual assembling and communicating dismounted archaeological elements. It includes a classification of elements which compose tangible and intangible heritage within a digital platform used to consult heterogeneous data. The core of the work is the definition of 3D/2D/1D models based on several surveying and representation techniques. Attention has been focused on the scientific advantages, costs, and precision levels guaranteed by various techniques, as well as on digital visualization as the fundamental element of the communication strategy.

Keywords: archaeological heritage, survey, 3D/2D/1D model, virtual reconstruction, database

Introduction

Innovative tools, which are constantly being developed, make it possible for the researcher to adopt an integrative approach favourable to everyone involved in the whole process of documentation (Bianchini *et al*., 2014). The work of documenting, analysing and interpreting archaeological heritage is conducted by various types of professionals: architects, archaeologists, art historians, computer scientists, etc. Currently, a strong need is felt for sharing the extensive knowledge obtained, knowledge which is still growing as a result of the continuous progress and the potentialities inherent in digital systems. This close collaboration between specialists made it possible to understand the key elements of archaeological heritage based on considerations extracted from historical analysis. At our disposal, we have a large quantity of information gathered by taking advantage of the potentialities of technologically advanced tools. What has recently been taking shape is the all-comprehensive approach, which can be adapted to comprehend archaeological artefacts on a large, medium and small scale, whilst at the same time take into consideration all the different competences involved and optimise the results obtained through concerted effort. Within this framework of study, analysing and contextualising an element or an archaeological site becomes the basis for any research. The nature of each object becomes easier recognised precisely thanks to the synergy of various different forms of knowledge and the complementary nature of various studies, which today are considered essential and directly related to the enquiry into and interpretation of *Archaeological Architecture*[1] (Bianchini, 2012a). Obviously all the parts involved in studies of this kind benefit from the advantages inherent in the integrated approach: architects because they can better understand the key elements of the original design on the basis of elements derived from a more profound historical analysis; archaeologists because they have at their disposal extremely detailed and reliable information. Furthermore, both have the advantage of innovative methodologies developed in the digital ambiance for interchanging, using, and sharing heterogeneous data, both in the stages of acquisition and processing. Any study undertaken with a method that incorporates the use of the above mentioned disciplines, allows one to construct a large database structured in the way that integrates the modalities applied in each of them (Gaiani *et al*., 2009).

The diffusion of information in the archaeological sector is founded essentially in representations focused on providing information concerning evolutionary stages, stratigraphy of the terrain, documentation of structural remains and of materials recovered during numerous materials. This information is, in turn, recovered

[1] Artefacts whose archaeological and architectonic values are inseparable

during numerous archaeological excavation campaigns and/or during field surveying and representation - as long as they concern architectonic and urban heritage — two-dimensional and three-dimensional elaboration[2] become indispensable for creating knowledge of the artefacts (Ippolito 2015). They provide data related to metric and dimensional aspects of the artefact, which also happen to concern the contextualization of the object under analysis, as well as to the material structure and the pathologies of degradation (Evans and Daly, 2006). The use of the two modalities and of different methods shows the importance of all efforts undertaken towards cataloguing the vast and heterogeneous quantity of data, which are constructed in the course of the studio experiments and referred to research. These data include 1D[3], 2D, 3D models, archive documentation, photographic documentation, and elaborations concerning the excavation processes that took place at different times and places. Moreover, cataloguing that deserves the name of exhaustive ought to include a lot of rough data — for its objective definition. This serves together with processed data — non-objective, filtered through the knowledge, abilities and sensibility of the operator. In point of fact, to think of a catalogue as complete is very risky in view of the fact that research is, in general, a continuous process and can never be considered completely concluded. This concerns especially archaeological research characterised by time consuming practical operations. The whole problem in its entirety, if it is to include different typologies of data, makes it indispensable to conduct a rich and orderly research of all relevant material. Specifically because subjects of archaeological interest are concerned within a system that can be continually and quickly implemented and taken advantage of, and this is open from the point of view of diffusion, this must rest on the basis of scientifically valid and rigorous data (Bianchini, 2012b). Within this frame of reference, the new technologies can play a significant role in different aspects of the term. Firstly, the techniques of mass acquisition make it possible to have at our disposal, objective survey datum which is exempt from selection. Then, the techniques for 3D acquisition, modelling, the modality for integral representation, and techniques of interactive visualization all go to improve the knowledge level of the object under study. Moreover, the development of ICT (Information and Communication Technologies) favoured all the more the use of digital technologies, which encourage us to use them and experiment with them because of reduced costs and easy application.

The objective is to implement and improve the activities that go to preserve, protect, valorise, and popularise Cultural Heritage where documentation has acquired a fundamental role (Van Dyke, 2006). The digitalisation of cultural heritage is today shaped to provide results primarily for different front lines: construction of three-dimensional models of real objects with a high level of similarity to reality, metrically correct and reliable; virtual reconstruction on different scales of objects that do not exist anymore; and the construction of digital archives (Gaiani *et al.*, 2011). Lately, the objective adopted is that of assembling and integrating all of this within single platforms in order to be managed and utilised by those involved in the research, and also by less specific applications. These considerations go to show that the potentialities and the advantages of various digital systems or archiving, data acquisition, model processing, and communication have been almost completely understood. Consequently, it seems easy to understand the reasons which have gradually lead to a change in the concept of representation. This is almost directly connected to that of information, as well as to the possibility of interrogation, and to the modalities of communication that characterise the various systems at our disposal (Apollonio *et al.*, 2011).

Transparency of information, of the sources and processes followed, becomes a necessity; especially in the field of archaeology. The study of its elements, whether it be entire sites or fragments of objects, is largely based on indirect information, comparative analyses, and interpretative hypotheses. The question of paradata[4] (Denard, 2009) and metadata[5] become more and more important for activities concerned with archiving, managing, sharing, and utilising digital resources related to cultural and architectural heritage (Bentkowska-Kafel *et al.*, 2010, 2012). In order to resolve the problems involved in *Archaeological Architecture,* one has to tackle them from the cultural point of view rather than for the technical one. This has to be done in such a way that operations and choices undertaken with the view to achieving the level of knowledge — more profound and structured — of the object of study will always be guided by scientific rigor. The sector of

[2] Geometric models lean toward the geometrization of elements to be represented, and yield information on morphology and spatiality of the object under study. Architectonic models describe reality through images of elements indicating the quality of surfaces and their state of conservation.

[3] All those textual, numeric and alphanumeric data describing objects, that allow us to define any three-dimensional and bi-dimensional ideal model in a virtual space.

[4] Paradata and metadata should be clear, concise and easily available. In addition, it should provide as much information as possible. Paradata is defined as: information about human processes of understanding and interpretation of data objects. Examples of paradata include descriptions stored within a structured data set of how evidence was used to interpret an artefact, or a comment on methodological premises within a research publication. It is closely related, but somewhat different in emphasis, to 'contextual metadata', which tends to communicate interpretations of an artefact or collection, rather than the process through which one or more artefacts were processed or interpreted.

[5] Metadata, considered as data about data, can help to organise information and provide digital identification.

digital documentation of cultural assets is expanding and archaeology seems to provide a vast field of application. Although its procedure has not yet been defined univocally, the processes of managing the data in the stage of acquisition (surveying) and processing (survey), as well as the modality of information archiving and disseminating, have been well outlined. The approach adopted here guaranteed the scientific character of the surveying and representation operations that underlie analyses and interpretation of elements under analysis.

The case study presented here concerns an important ancient archaeological context: the Etruscan Sanctuary of Pyrgi (Santa Severa, Rome) (Colonna, 1970, 1985). Attention has been given to the study and analysis of archaeological elements that are parts thereof, by applying methods and techniques which make for an understanding of the objects at the urban scale and in full detail (Colonna and Pelagatti, 1990). Therefore, presented here are the processes followed as well as the results of some experiments with the object, to bring out important aspects of the concerted efforts of architects and archaeologists. The study presented here is situated within the ambience of survey, conceived as a structured system capable of organising diverse information, such as tests, images, 2D and 3D models, as well as of representations conceived as an instrument for describing, popularising and communicating information related to cultural heritage. The objective is to present the way in which digital technologies allow us to document, preserve, evaluate and popularise cultural heritage by structuring an 'open' system of cognition, and therefore always lending itself to implementation.

Temple A of Pyrgi: knowledge

The research presented here was possible thanks to the contribution of the Institute of Etruscology and Italian Antiquity of the Sapienza University of Rome.[6] For years, it has studied the Etruscan sanctuary in its different aspects, from its urban and territorial ambience and its connections with the port of Caere, to the analyses of the fragments of architectural terracotta.

Excavations conducted in 1957 brought to light a sacred area upon which there stood two temple complexes, named Temple A and Tempio B, endowed with rich architectonic ornamentation. Area C is well known as the place where gold foils were found and a rectangular edifice divided into cells places against the enclosing wall of the sanctuary. Only a few vestiges of the temple context survived on the site of the temple complex, but numerous fragments of decorations have been found[7] (Baglione *et al*., 2013). Part of the archaeological material discovered is today exhibited in the Museo Nazionale Etrusco di Villa Giulia in Rome and at the Antiquarium of Santa Severa.

The aim of the study is to valorise cultural heritage by enquiring into the possibilities and the modalities for documenting and popularising architectural heritage. The present endeavour was taken up with the intention of implementing a process never before attempted in relation to the data concerning the Sanctuary of Pyrgi. This process takes into account that there are not only existing architectonic materials, but also historical documentation, data gathered by archaeologists, drawings made during various excavation campaigns, interpretative hypotheses, including in a vast cataloguing effort tangible and intangible elements of the heritage.

Temple A of Pyrgi: digital documentation

The present work has two principal purposes: firstly to meet the current necessity to popularise data concerning archaeological heritage through digital technologies applied, starting with the stage of data acquisition; and secondly to provide a reconstruction in virtual ambience of the architectonic organism, which is extremely fragmented and whose present state is irremediably damaged by the conditions of the place where it is located.

The focus of interest is based on the definition of three-dimensional models and on the digital visualization. These are the basic elements of the communication strategy, in clear contrast to the modality of communicating information in the field of archaeology (Molyneaux, 2011; Guidi *et al*., 2013). A point of fact is that even through more recent experiences undertaken we observe a passage from the techniques of analogue representation in favour of the digital ones, a major part of documentation still relies prevalently on texts, while the graphic models are hardly included. Therefore an attempt is made at defining the significance of developing and applying a digital platform conceived as a place of expeditious consultation of data that integrates textual information with 2D/3D models for different users. The starting point was existing archaeological documents integrated with three-dimensional models of structural remains and the architectural terracotta stored in various museum sites. The models were obtained through the operation

[6] Prof. Maria Paola Baglione, Dott. Barbara Belelli Marchesini.

[7] Three documents carved on gold tablets found around Tempio B on July 8th 1964 during an excavation campaign go back to the VI or the beginning of the V century before Christ. The remains are of considerable historical and linguistic interest for Etruscan archaeology, and are considered to be the first sources written in italic languages. Today they are housed in the Museo Nazionale Etrusco in the Villa Giulia in Rome.

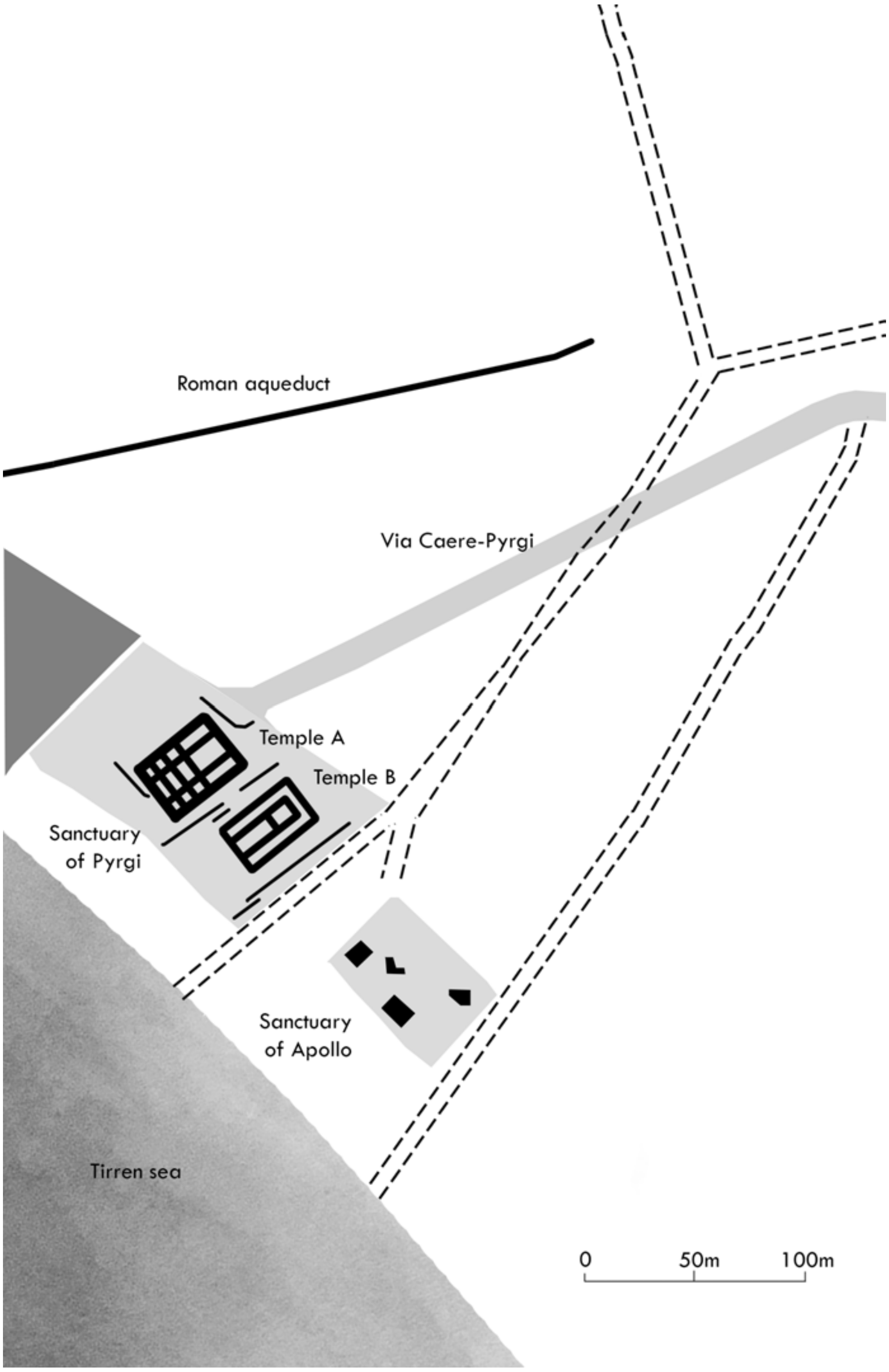

Figure 1. Archaeological site of Pyrgi (Santa Severa, Rome).

of no-contact surveying with low cost instruments, which make use of the advantages provided by DSM technology[8] (De Luca, 2011). Moreover, compared and integrated with this was the information derived from topographic survey of the structural remains and the information deduced by archaeologists, reported in their excavation notes which are today systematised into volumes of indispensable knowledge for the object analysed.

This type of process is oriented towards a systematisation and diffusion of mixed information that includes information gathered in order to diffuse as much as possible the knowledge of the object,

[8] Dense Stereo Matching technique offers the possibility to generate 3D content from photographic images without the need of high-cost hardware. The DSM technology originates in the theory of photogrammetry and makes it possible to draw 3D graphic models on the basis of photographs. Through DSM technology it is possible to obtain a realistic three dimensional rendition of architectural elements on the basis of a global and coherent integration of all survey, modelling and the stages: coordinates, distances, vertices and profiles for the reconstruction of 3D models, texture.

documentation of the present state, reconstruction of a reality completely lost (Callieri *et al*., 2015; Remondino and Campana, 2014).

The work presented here is focussed on Temple A, and has been articulated into the following stages: recognition and analysis of all the material at our disposal; arrangement of the existing documents according to the document typology (text, images, archaeologist's drawings, 2D paper models, physical 3D models); integration of information at our disposal with data obtained from surveying/survey of existing objects; present semantic classification of material in relation to the case study; and virtual reconstruction. The documentation thus obtained — of exclusively digital nature — makes it possible not only to recognise the state of conservation of the object studied and to preserve — be it solely in the digital mode — a site most probably destined to disappear, but also to reconstruct the original shape of the elements that are already lost.

The systematisation of these data within a single system/platform as well as their diffusion are part and parcel of Digital Heritage as defined by the Charter on the Preservation of the Digital Heritage published by UNESCO (UNESCO, 2009). This is the 'technical, medical and other kinds of information created digitally, or converted into digital form from existing analogue resources including different kinds of products such as texts, databases, images, audio, graphics, software and web pages'. Preservation of cultural heritage through digital modalities for managing and visualizing raises problems of a different order, linked to the transparency of operations carried out in the different stages of the process. It therefore concerns all the disciplines involved.

In the first place, the initial data have to be as clear as possible as they delineate the criteria adopted for cataloguing (Batley, 2005); secondly, they have to guarantee correctness and the scientific nature of the process followed for acquiring and processing of survey data within the framework of digital reconstruction; and finally, appropriate modality has to be found that will guarantee the use of the system structured in this manner and in the function of various interpretation levels.

The recourse to systems for acquiring and extracting heterogeneous information (graphical, textual, historic-biographical, 1D, 2D, 3D models) which make use of the potentialities of methods, techniques and instruments adequate for the digital era is considered to respond to the problems connected with information diffusion within the field of archaeology, putting forth innovative and interactive modalities for the diffusion of new contents.

A complete and organised collection of archived documentation — graphic and textual — as well as cataloguing of data at our disposal, were necessary to maintain unchanged the informative contents while passing from textual archaeological documentation, to that with a large number of graphic models. The criteria adopted for cataloguing objects are strictly connected to the characteristic properties of archaeological objects: registered name, historical period to which the object belongs, and a list of documents concerning Temple A. Such a classification made it possible to structure documentation, and having started with semantic classification of the component parts of the object of study it links indissolubly their cognition to the study of the sources at our disposal and to archaeological interpretation, the objective being the construction of models which are as objective as possible (Brunetaud *et al*., 2012; Apollonio *et al*., 2013).

Familiarity with the methods and techniques for data acquisition legitimised an a priori assessment of the results to be obtained through surveying various existing objects (structural remains and fragments of architectural terracotta). These in turn constitute a solid basis for understanding the whole organism, combined with the survey of the intangible carried out by studying texts for the purpose to construct theoretical models. Such an operation aims at implementing the documentation already available, although incomplete and heterogeneous, and at times composed of information contradictory to valid 2D/3D models. Recourse to three-dimensional models in archaeology can have quite a number of repercussions for the diffusion of information, which is not always achieved on a large scale for reasons of space and costs. That is exactly why integrated methods for low cost surveying have been adopted. The processes of acquiring and elaborating data have been conducted through integrated surveying with the application of DSM to construct models and to carry out direct surveying for controlling measurements. Data acquisition and processing through DSM concerned two typologies of elements (Zheng *et al*., 2008). On the one hand were those useful for an ideal reconstruction of Temple A, from which profiles have been extrapolated and geometries reconstructed; on the other hand there were those sculpted, but excessively fragmented materials which are un-attributable to any architectural typology. On the basis of this choice, such elements could be catalogued through photographic images or survey elaborations executed by applying traditional methodologies. Furthermore, with the help of three-dimensional models correctly scaled and placed in the Cartesian conception of space, these fragments can be placed in the visualized object. They are useful for putting forth reconstructive hypotheses on the basis

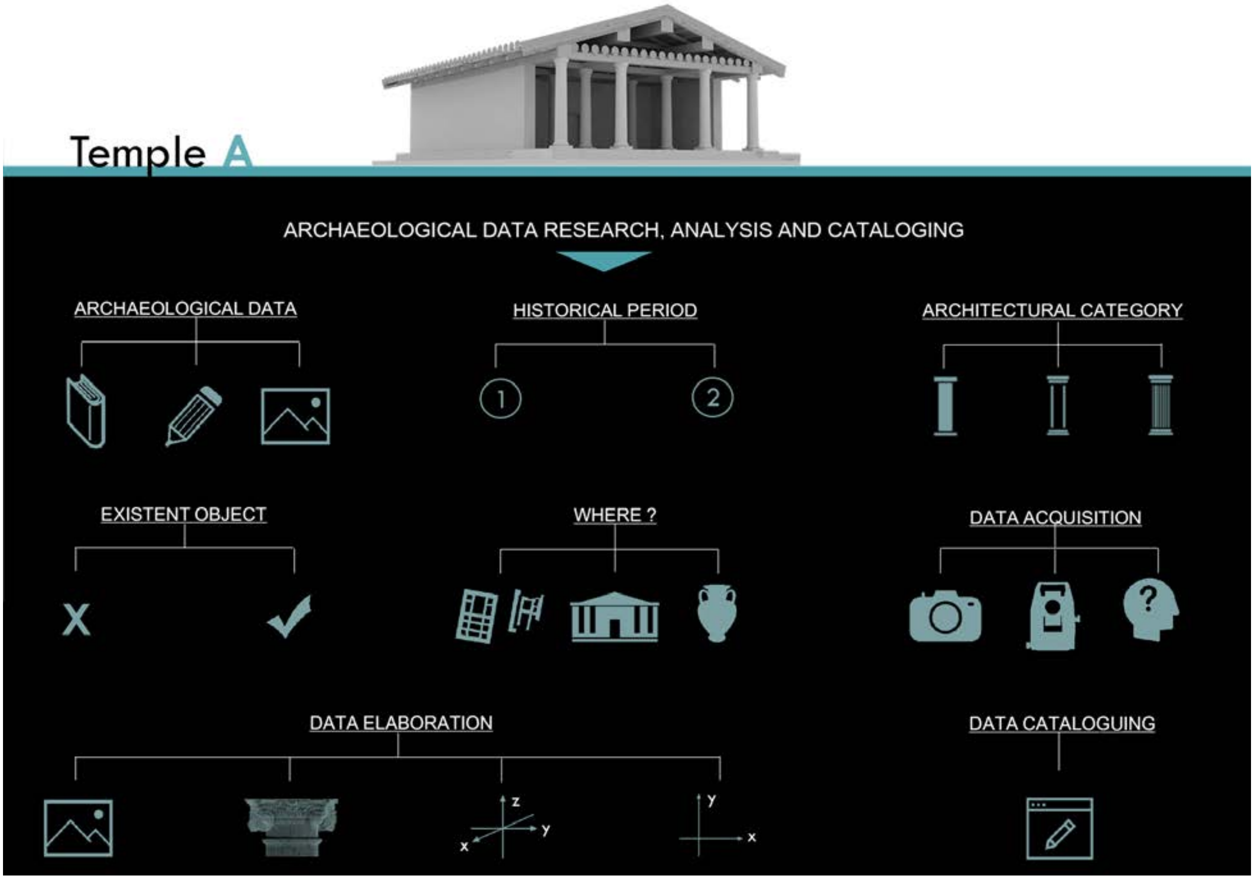

Figure 2. Archaeological documentation.

of data which is objective metrically, geometrically, chromatically and materially.

The example presented below shows operative procedures employed in the stage of acquiring and elaborating all existing fragments. The object of study is a high relief sculpted with mythological motives (that of *Seven against Thebes*), situated on the back side of Temple A. Its archaeological aspects have been studied for a long time now because of its complexity, the significance of the theme depicted, or for very particular and orienting photograms obtained from the chosen software to process images with the polychromy, which is its characteristic feature (Colonna, 1996). After numerous efforts, the element has been completely restored and is now treasured in the Museo Nazionale Etrusco di Villa Giulia in Rome. By carrying out the project it was possible to establish the minimum number of photograms to be used, taking into account the required overlapping of at least 30% in order that the software could recognise homologous points in different photos. Detail and uncertainty levels are linked to the intrinsic characteristics of the camera as well as to the external conditions of lighting and accessibility to the context in which the object is immersed. In order to adequately recover all the elements of the object, the distance of the shots has been calculated on the basis of the lens focus and the typology of the camera used. Uncertainty has been managed through measurements acquired by direct surveying and also by correcting optical aberrations of particular photograms — the stage preceding the construction of the three-dimensional model (Cipriani and Fantini, 2015).

Photo-modelling imposes the integration of automatic procedure for alignment procedure in which the operator must have a full knowledge of the determining processes: data purification, mesh optimisation, orientation and scale of the model. In this way, a 3D model of high fidelity to the real object is constructed, and makes it possible to recognise even the minutest discontinuities and distortions, and can be applied to grasp the geometric and qualitative characteristics of the object and to extrapolate 2D profiles and models.

In this stage, conceived for reconstructing partial models, all the problems connected with the acquisition

Figure 3. Analysis and cataloguing of archaeological data: tangible and intangible heritage.

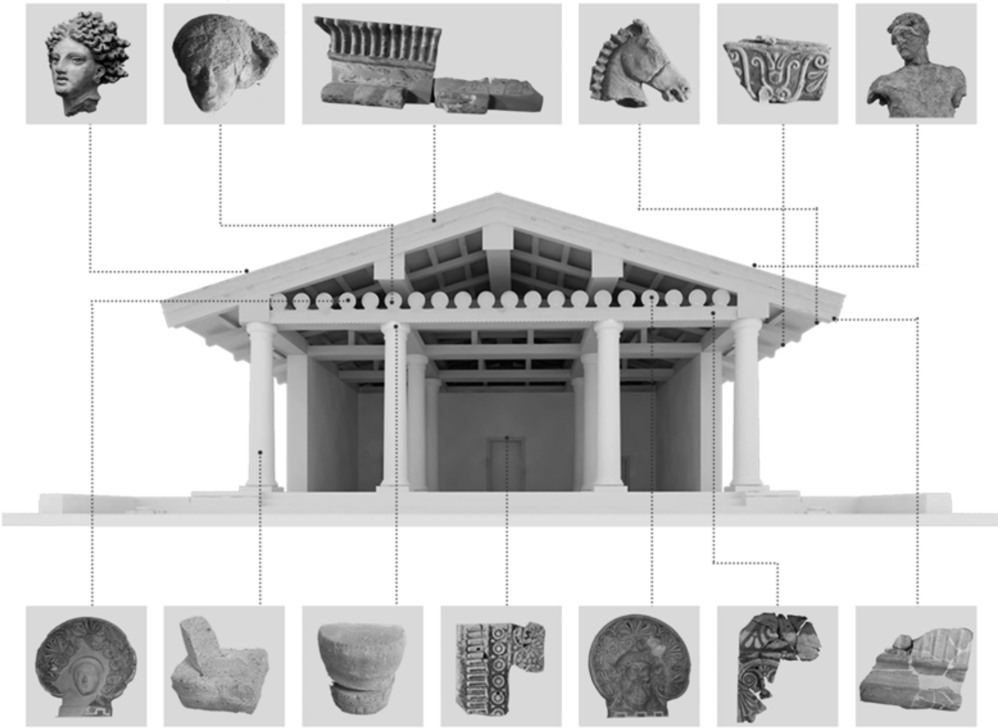

Figure 4. Temple A, some architectural terracotta.

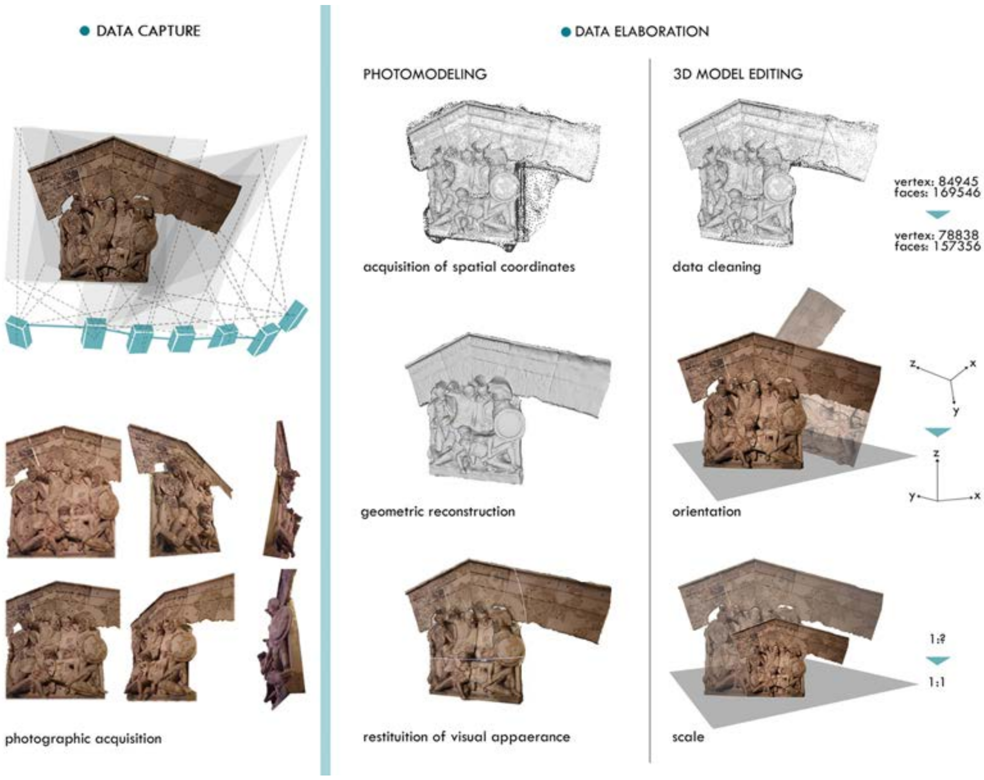

Figure 5. The mythological high relief; 3D data acquisition and elaboration.

Figure 6. The mythological high relief; detail of numerical model, mesh model, texturized model.

process have been addressed: defining the number of photographic shots in relation to the dimensions and complexity of the objects, to their accessibility as well as to the lighting conditions in the museum where they are exhibited.

The successive stage, however, concerns three-dimensional reconstruction of Temple A in virtual ambience. The model — the synthesis of the knowledge derived from the study and analysis of the data gathered — had been defined in the construction elements and then in the decorative ones. At this stage a confrontation between researchers who work in different fields of endeavour — archaeology and architecture — is considered fundamental (Vrubel *et al.*, 2009). Archaeologists' contribution was fundamental in order to determine geometric matrices of objects, while thanks to surveying and representation it was possible to construct the model in accordance with scientific criteria.

The construction of an ideal model, based essentially on virtualizing archaeological data, rested upon digital methodologies for two-dimensional representation and for three-dimensional modelling. Defining, generating, and directing profiles and curves made it possible to reconstruct the most probable original aspect conceived for Temple A at the time when it was built (Bourke, 2012).

The problems addressed in strict collaboration with archaeologists are related to the interpretation of the dichotomies between data obtained from different sources in the total composition of the object, between the passage from the complexities of the architectonic object to that of single pieces and decorative elements, and the choice of detail level.

The worked out model was then applied to verifications connected with metric-proportional and structural aspects and as the spark for reflection leading towards the definition, description and understanding of decorative elements. This seems to recognise the features of the whole complex, making critical interpretation easy, and based upon and facilitated by an exhaustive representation as it is currently possible to make. The road taken was to '[...] *to recompose the spatial "box" , analysis of its constitutive parts, their classification and description as well as, finally, the verification of possible rules underlying diverse combination of elements*' (Docci, 1989).

Transparency of reconstruction determines the quality level and the scientific rigor of all applications and studies of virtual archaeology (Koutsoudi *et al.*, 2014), therefore the criteria followed were delineated by inserting them inside the informative database pertinent to Temple A.

In order to guarantee the scientific nature and reliability of the procedure, three typologies of elements have been distinguished: certain (remains of the archaeological site), secure or highly probable elements repeatable or speculative, elements which are possible to extract from surviving structures or decorations; elements extractable from prior reproductions whose possible errors or misinterpretations have to be ascertained); and finally deduced elements (possible to determine from structures or decorations belonging to similar edifices or by typology, characteristic features and historical epoch).

Temple A of Pyrgi: Communication

Both typologies of models achieved, totally reconstructive and partially derivative from surveying, have been used as an instrument of communication between various professionals involved in the research before the instrument in question was applied by external users.

The bases of data described above constitute modalities for gathering and presenting — in a transparent manner — the whole process carried out including objectives, methodology, techniques, arguments, characteristics of research sources, results, and conclusions[9]. Such a principle reaffirms the necessity to prepare the documentary objective and the exhaustive basis that concerns the whole research process related to creating digital contents in projects of virtual architecture. The base of data constituted represents the point of departure for the road leading to a complete knowledge. Digitalisation makes it continuously and immediately applicable, and useful for faster and

[9] Principle 7.1 of the Carta di Siviglia.

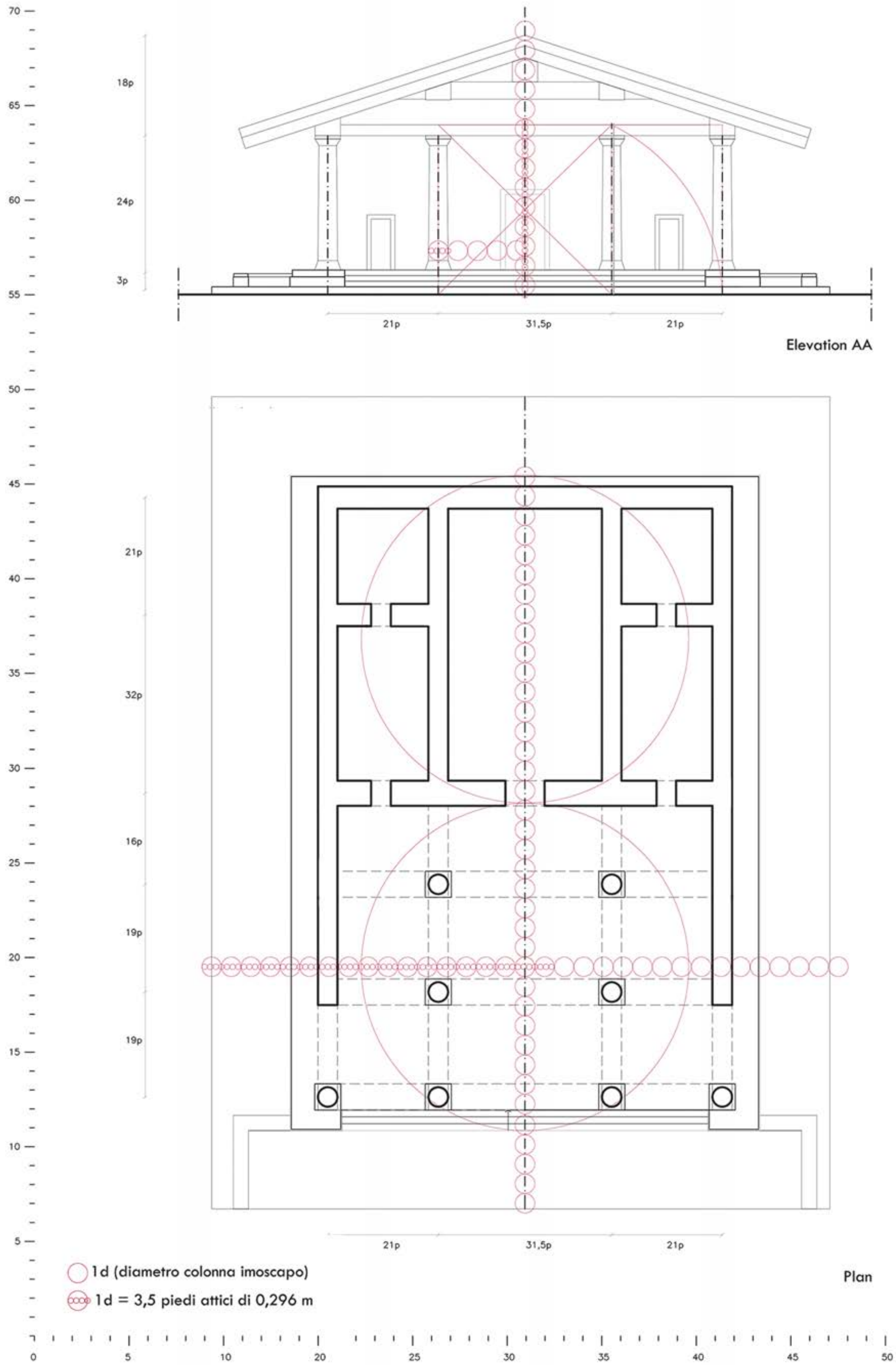

Figure 7. Metrological analysis.

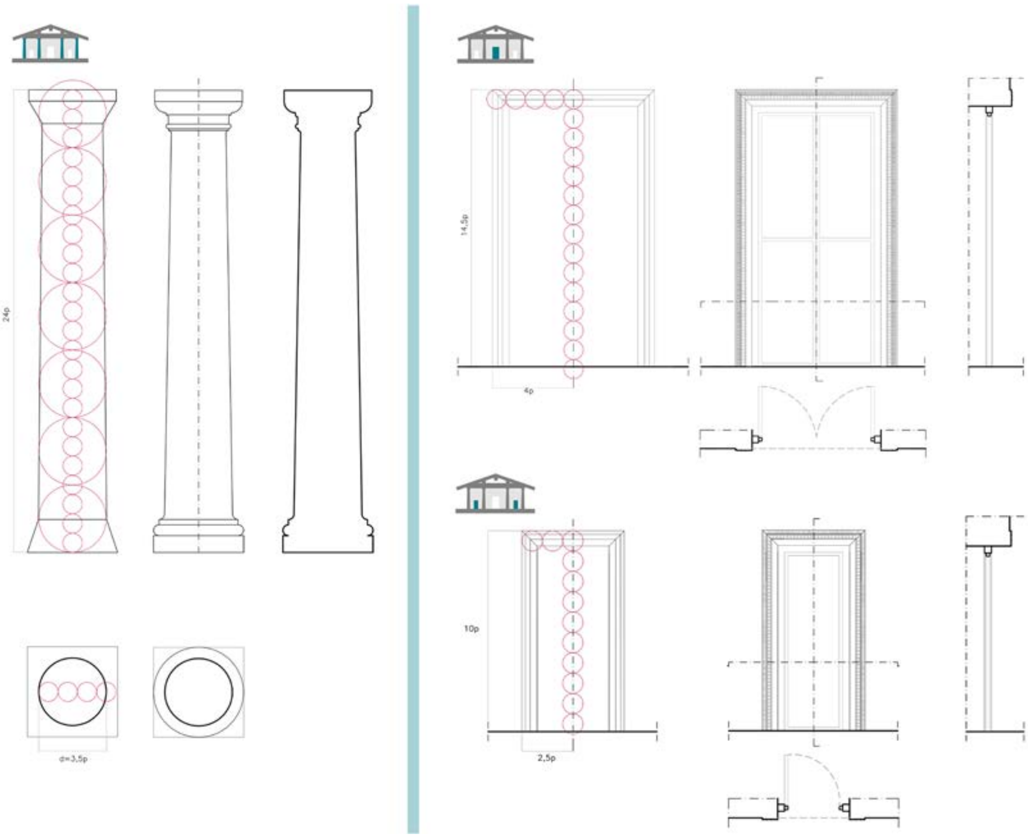

Figure 8. Virtual reconstruction, proportioning architectural elements, 2D models.

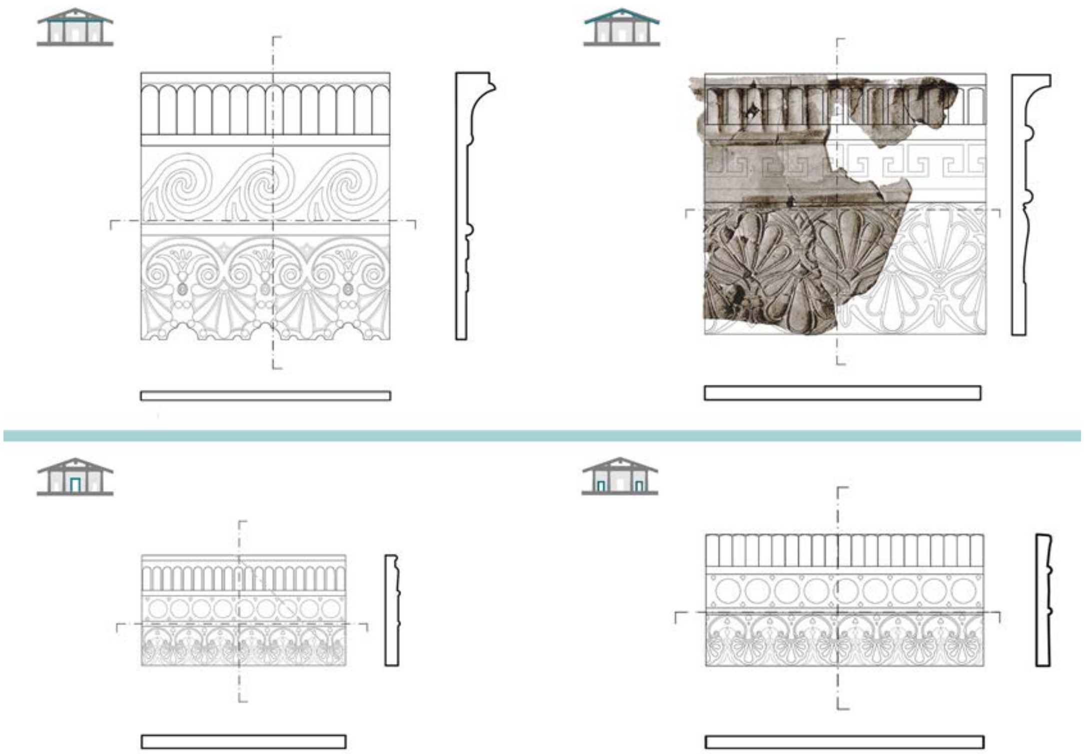

Figure 9. Virtual reconstruction, proportioning architectural elements, 2D models.

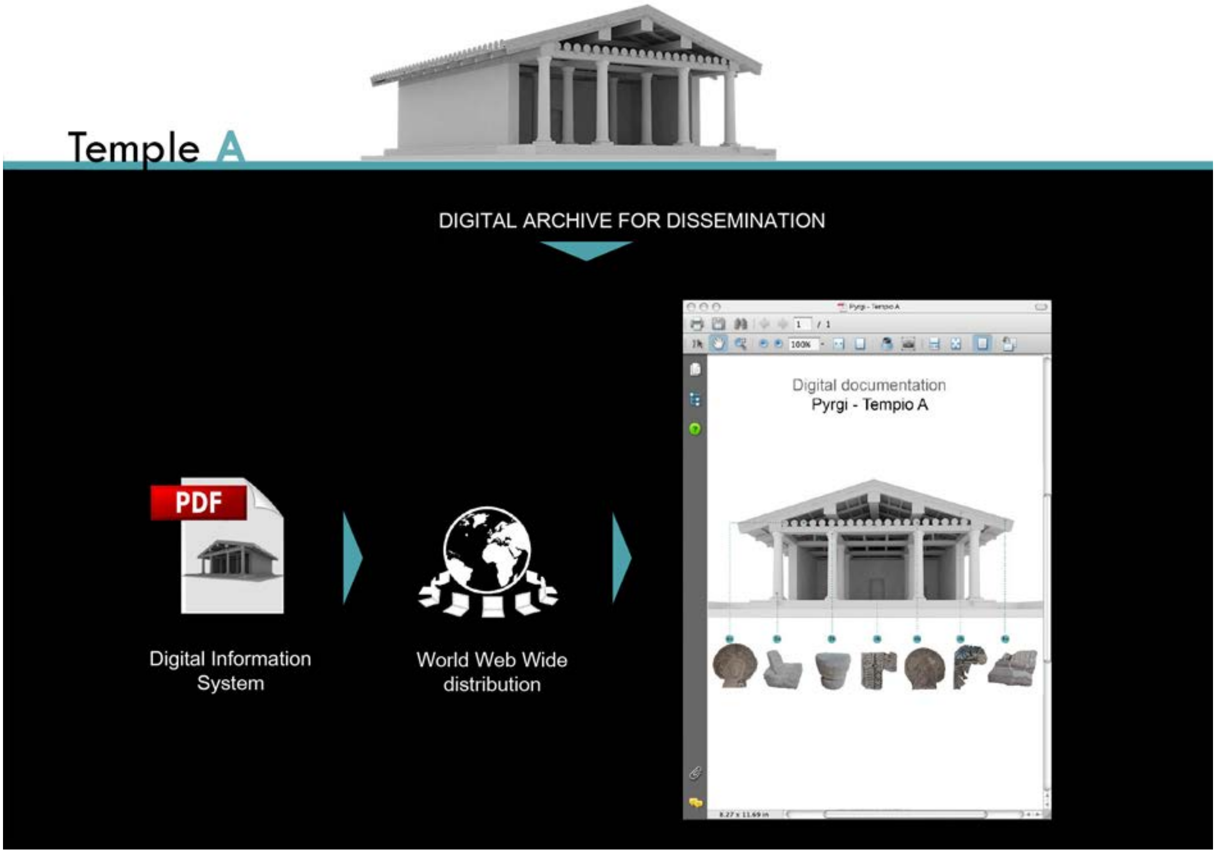

Figure 10. Digital archive, 3DPDF.

simpler dissemination of heterogeneous contents: data sheets with information on existing objects, graphic 2D elaborations, 3D models, photographic images, multimedia contents, and virtual itineraries. Both 2D and 3D models were constructed with two objectives in view, which imposed the necessity to distinguish figurative models from those prepared for scientific purposes. The aim of figurative models is to convey the research into mimesis: their objective is to provide documentation similar to reality for purely educational purposes. Similarity to the real object, it has its source in the geometric recognisability of individual parts and in the application of texture, integrating formal information with material and chromatic features, which establish a relationship with reality from the point of view of perception. Models created for scientific purposes, on the other hand, are characterised by well-defined geometries and a high level of metric precision strongly connected with the definition of scale reference.

Constructed in this way a digital archive opens up the possibilities to score important results in the field of documentation and valorisation of archaeological heritage elements useful for achieving purely didactic and valuable objectives for institutions and professionals involved in the protection of cultural heritage. The construction of a digital archive implies the necessity to ponder a few issues: how to connect heterogeneous information, how to put questions to the system, and which applications to use. A first test was done with the software Adobe Acrobat PDF.[10] The fundamental subject is the definition of connections between data structured according to semantic categories and able to organise different information, like texts, images, 3D/2D/1D models linked by transitive relations that make the transition from the general to the particular possible, and from the simple to the complex.

Conclusion

An approach open to various disciplines makes it possible to be critical of the stratified contexts so characteristic of the field of archaeology, and from it extracting information that allow us to understand and analyse them. Defining an open system based on the integration of specific and heterogeneous competences involved in the study of archaeological heritage provides the point of departure for structuring a process whose objective is cognition (knowledge or cognition and knowledge). Survey and representation

[10] https://get.adobe.com/it/reader/

become indispensable for analysing, interpreting, and documenting cultural heritage, and the efforts of architects and archaeologists guarantee quality elaboration of the final Product. Moreover, the application of all the more innovative technologies ensures the possibility to exchange objective data which is open to further interpretations. Every project that aims at the virtualization of archaeological elements is in part a process which comes to be articulated in the knowledge of the current state, and in putting forward interpretative hypotheses upon past events during the existence of the artefact. The methodological stage, as well as the practices that lead to the construction of models and database creation, rest upon objective and highly interdisciplinary operations. This latter feature is of determining value, not only for reconstruction, which is the domain of virtual archaeology, but also for public administration, engineering companies, and events organised within the sector of cultural tourism.

The structure of any computerised system places at our disposal detailed and complete documentation, and makes it possible to diffuse the results obtained from survey operations and three-dimensional model construction by shaping them in various modalities. These become accessible to various, generic, or specialised users according to their needs. Digital instruments open up the possibility of establishing a continuous relation between iconicity and visualization of the object surveyed, formalised via models that provide various possibilities linked to the use through various scales of representation (from 1:1 to 1:∞), different interpretation levels, for purposes that lead to changing knowledge, its diffusion, and research. In this way, a system is structured — rigid, but dynamic and complete in its contents, based on the transitive use of various models. Thanks to a high similarity level in relation to the real object, the constructed models have been used as instruments for understanding and communicating the object under analysis. Survey proves to be an indispensable tool for analyses, documentation and critical interpretation of archaeological artefacts on large, medium and small scale. At the same time, the joint contribution of architects and archaeologists and the application of innovative technologies guarantee high quality of final product elaboration and makes for an interchange of objective data open to later interpretations. Elaboration of models for static and dynamic representations of objects as well as creating databases for interactive use online, constitute a model for managing archaeological heritage with the following objectives in view: cataloguing and valorising cultural heritage, creating scientific educational documentation, and the diffusion of information in a structured and interactive manner. The latter idea is strictly connected with the problems involved in public interchange and diffusion of data with formats of extensive diffusion through data banks that are more and more accessible, complete, applicable, and usable from a distance precisely because they have been digitalised.

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New Actualities for Mediterranean Ancient Theaters: the ATHENA Project Lesson

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Abstract

Ancient Theatres are one of the most extraordinary legacies that past civilizations have left us. From cultural standpoint, this is because of the importance that these monuments had in the social life of each past community; from the environmental standpoint, because of the enormous skill that went into controlling the territorial and urban impact of these 'structures'; and finally, from a 'technological' and functional standpoint, because of the excellence of their internal distribution patterns and acoustics, which are hard to equal even today. In this paper we present the activities of the Ancient Theatres Enhancement for New Actualities (Athena) Project funded by the EU within the Euromed Heritage IV Program. A project addressing six famous sites on both shores of the Mediterranean (Mérida, Petra, Jerash, Carthage, Cherchell, and Siracusa) providing a special focus on the documentation, reading, representation, analysis and also some innovative ways to involve the general public through user–friendly instruments and outputs.

Keywords: Ancient Theaters, survey, 2D/3D models, constructive geometries

Introduction

Ancient Theatres are one of the most extraordinary legacies bequeathed to us by the Greek-Roman civilisation: culturally, due to the important role they played in the social life of several cities; environmentally, due to the criteria and care taken to optimise the impact of these structures on the territory and urban context; and technologically and functionally due to the quality of their acoustics and layouts. These very diverse sites with their independent, unique architectural types (roughly 1000 in three continents!), as well as the many theatres still used as performance venues, are scattered far and wide: from Portugal to Afghanistan, from Egypt to the north of England (Anti, 1947; Caputo, 1947; Neppi Modona, 1961; Ciancio Rossetto and Pisani Sartorio, 1994–1996).

The interest and 'success' of Ancient Theatres among the public at large is certainly one of their strong points and the key reason why they survived. However, this success is also the primary reason for their decay. The relentless pressure exerted on these structures by the passing of time, exceptional natural events (geological, meteorological, etc.), contemporary use (tourism, performances, setups, etc.) and war-related or socio-political events were unfortunately increasingly frequent, leading to the slow, but often irreversible deterioration of these architectures (Fiechter, 1914; Ciancio Rossetto and Pisani Sartorio, 2002).

Since the Declaration of Segesta of 1995 twenty years ago, many steps have been taken to develop a strategy that will allow us to enjoy these theatres in the future and allay the risks associated with their use (Tosi, 2003; Pappalardo and Borrelli, 2007). The *Siracusa Charter for the conservation, fruition and management of ancient theatrical architectures in the Mediterranean* (2004)[1] is undoubtedly a major step forward, especially because it moves beyond the usual statements of principles. It has proved to be truly valuable, including operationally, in specific activities implemented by those involved in the management of Ancient Theatres (Pedersoli and Paronuzzi, 2010).

It is this cultural rather than strictly scientific context that triggered one of the most important practical effects of the Siracusa Charter: the ATHENA Project (*Ancient Theatres Enhancement for New Actualities*). The Project was financed in 2009 by the European Union as part of the Euromed Heritage IV Programme.[2] It

[1] http://www.univeur.org/cuebc/downloads/PDF%20carte/18.%20Carta%20di%20Siracusa%5B.pdf

[2] The ATHENA Project (2009–2013, with a budget of roughly 1.8 million euro, www.athenaproject.eu) was financed by the European Commission as part of the Euromed Heritage IV Programme (www.euromedheritage.net), the fourth step in an intervention package originally created by the EU in the framework of the MEDA programme and under the supervision of the EuropeAid Cooperation Office. Since 1998, Euromed Heritage has spent roughly 57 million euro in the field of Cultural Heritage, financing cooperation projects between various actors from different countries in the Mediterranean (research agencies, universities, administrations, scholars, local

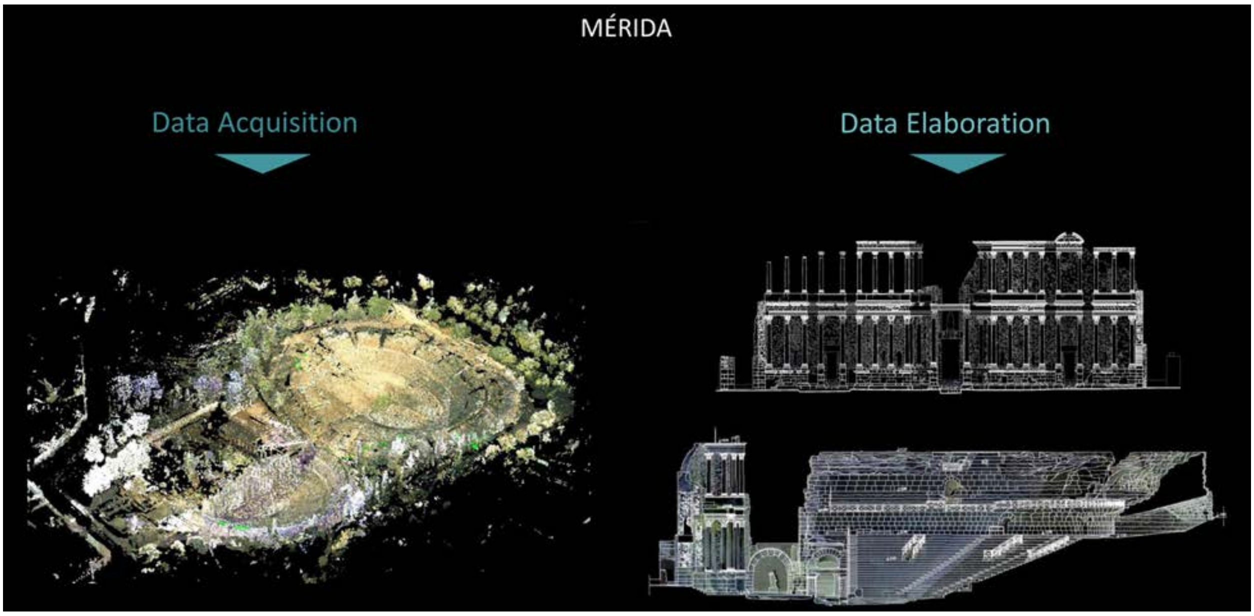

Figure 1. The survey process: from data acquisition to data elaboration.

has helped to draft a new, updated strategy for the documentation, conservation, enhancement and sustainable fruition of theatrical structures by turning some of the recommendations in the Siracusa Charter into concrete actions (Bianchini, 2012). Not just as proposals or design projects, but by working '*in corpore vivi*' in six particularly emblematic sites in the UNESCO World Heritage List (Mérida, Siracusa, Cherchell, Carthage, Petra, and Jerash).

This research is also a contribution to *Survey,* which is considered as a *knowledge tool to understand material elements*, i.e., the process that materially envisages the establishment of a suitable knowledge system to *Acquire, Select, Interpret and Represent quantitative* but above all *qualitative* data. If the former (essentially from surveys) can/must be performed to the greatest extent possible within the boundaries of a strict scientific approach, on the contrary the latter (the result of critical observations) depends on the sensibilities and interpretative skills associated with the choices, selections and representations decided by an actor.

This is an intrinsically multidimensional and multidisciplinary process[3] which in the case of built objects (architectural, archaeological) involves not only the study of their *material* characteristics (space, construction, art) and *immaterial* characteristics associated with their use, but also their history and cultural and social context. In some ways *Survey* involves capturing the intimate essence of material elements and understanding their structural matrix and proportional ratios. *Survey* also captures that which is often hidden but nevertheless linked to the immaterial culture which, over the centuries, has produced, transformed, preserved and finally enhanced those elements (Brunetaud *et al*., 2012).

In this regard, the survey process is closely linked to the epistemological concept of *model,* considered as the outcome of the operation performed by an *actor* on an *object* to extract some of its endless data. As a result the model is always incomplete, abstract and above all *subjective*; only the effects and outcome of *representation*

communities, etc.), actors who are involved in one way or another in the documentation, conservation and management of Cultural Heritage. Almost 400 partners on both sides of the Mediterranean have benefited from the first to the fourth Programme and, currently, the last edition.

[3] A multidisciplinary approach is now a basic requirement in any study, while as far as multidimensionality is concerned we should examine several fundamental concepts linked to the so-called culture of the control, in which it is possible, amongst other things, to identify the following principles: human beings have an innate or acquired ability to mentally imagine the qualities of physical space; from amongst the n qualities of physical space, geometric qualities optimise control and manipulation; manipulation and modification of space become tangible thanks to correspondence between the real object and its geometric abstraction (Geometric Model); when the Geometric Model is subjected to the representation process according to the rules of the science of representation, it becomes a two-dimensional Graphic Model and drawing is the tool that ensures the efficiency of the mechanisms of control and manipulation of the graphic model; when the Geometric Model is virtually reconstructed using modelling software it becomes a 3D digital model. Based on this approach, the multidimensional reality of a given object is reduced to its geometric essence, i.e. the Geometric Model made up of points, lines and surfaces which, appropriately scaled on the support and then projected and sectioned, in turn produces the graphic representation. In other words when it is reproduced in virtual form it creates a 3D Digital Model. In any event, this procedure establishes a biunivocal correspondence between the object and its virtual substitute on which to simulate any number of operations as if they had actually been performed.

make it available to others so long as they are able to interpret the representation code (Figure 1).

Choosing the right model (and hence the set of objectual data to be selected) and representation code depends on the quantity of positively communicated data. The advent of digital systems has added new *three-dimensional model* to traditional (intrinsically 2D) graphic models. These new 3D models are purely numerical representations which, however, are capable of establishing a very precise correspondence between physical and virtual space.[4] Furthermore, they are basically free of the dimensional constraints imposed on a traditional drawing by the limited size of the support. However, the digital revolution has also influenced the field of Survey, above all as regards the Data Acquisition phase. In fact, we now possess a whole range of tools and technologies that in just a few short seconds capture the geometry of any object, with errors that are easily less than one millimetre and without losing any information regarding the most important characteristics of the surface (colour, reflectance,[5] etc.).

Given the above, the research on Ancient Theatres constituted both the scope of our study and also a pretext to analyse the state-of-the-art of the whole field of Survey (Bianchini *et al*., 2015). No one can deny there is a clear-cut boundary between acquisition/ representation procedures — all generally focused on 'maximum objectivity' — and interpretation, that is instead the phase during which the subject remains the protagonist. Having established this boundary, some segments of the process appear capable of overcoming the stringent requirements imposed by the Scientific Method.

Nevertheless, there is a feeling that we now find ourselves, as we did roughly twenty years ago, at the threshold of another strictly technological and procedural leap forward. The Data Acquisition phase obviously includes the concept of *measurement*, i.e., the operation that makes it possible to translate the *quality* of a phenomenon into a *quantity* expressed using numbers derived from the relationship between the quantity surveyed on the object and the chosen unit of measure.

Nowadays the surveying is structured on massive data acquisition (3D laser scanning, Structure from Motion–SFM). It raises the issue of how surveyors interact and manage these technologies and devices. All operations that envisage the gathering of knowledge need to have a reference framework both vis-à-vis the data acquisition method (surveying) and the selection, processing and representation of the acquired data (survey).[6]

Data capture

Any study focusing on archaeological elements — whether at urban, architectural or detailed scale — is based on the creation of a Knowledge System involving the collection, interpretation and filing of data. A well-structured knowledge system has several components that can be grouped in *quantitative* and *qualitative*. If the first can (and should) be collected using a strictly scientific approach (i.e. an integrated survey), the latter involve instead the sensitivity and interpretative ability of the scholar who, at times spontaneously and intuitively, is capable of reaching levels of understanding that go beyond the simple act of taking measurements.

The structure of a meticulous, complete and correctly organised Knowledge System plays a key role in a complex knowledge process. The database must therefore satisfy the scientific criteria[7] widely established and accepted by the community of scholars. Given the above, surveys are not only instruments to gather in-depth knowledge[8] of the artefacts, they also represent the method required to extract the most suitable, correct data from reality.

The use of traditional survey instruments and procedures has often been hampered by the physical difficulties associated with covering an archaeological site that is either very big or has complex geometries. Recent technologies, such as 3D scanning or SFM allow surveyors to acquire all the points needed (counted in billions by now) to provide a good description of the

[4] Each material point P_r identified using its coordinates x_r, y_r, z_r in real space, immediately finds its virtual equivalent P_v, also identified by a univocal triplet of Cartesian coordinates x_v, y_v, z_v

[5] Reflectance indicates the portion of incident light that a given surface is able to reflect. The value has a physical significance associated with the characteristics of the material when its surface is hit by the scanner.

[6] For more details on computer-based visualization of Cultural Heritage see The London Charter, version 2.1 (http://www.londoncharter.org/fileadmin/templates/main/docs/london_charter_2_1_en.pdf).

[7] Karl Popper acknowledged the intrinsic inappropriateness of the tools available to humans so that they can understand reality and, ultimately, the very real inability to 'positively' demonstrate any statement as true. As a result he shifted the barycentre of knowledge towards proving that something is false. Popper believed that any theory is scientific only if it is possible to consider experimental activities as having the following objective: to demonstrate its inadequacy, i.e., its falsity. Based on this hypothesis, the study of a phenomenon is considered scientific only when a set of techniques is used and the latter are based on collected data that is observable, empirical and measurable, with an established level of controlled and declared level of uncertainty; it must be possible to file and share this data as well as allow it to be independently assessed; the procedures must be repeatable so that a new set of comparable data can be collected.

[8] The approach to knowledge expressed by the philosopher René Descartes distinguishes between normal knowledge, achieved only by our senses, and profound knowledge, achieved by scholars using only study methods and techniques that can demonstrate to the mind what is precluded to the senses.

surfaces without having to establish in advance which surfaces need to be measured.[9]

Since each archaeological site has its particularities, it is impossible to establish an absolute rule regarding the way a survey should be performed (Callieri *et al.*, 2015). Nevertheless, all the methodological options are analysed and developed during the *survey project* in order to optimise the operations vis-à-vis the objective. As a result, elaborating a survey project is a key stage in the whole process. A correct survey project (partly) guarantees the quality of the data later used to produce the survey drawings; it also ensures the accurate gathering of numerical data obtained only from the measurement operations and still not processed.

In this study, we decided to use an integrated 3D survey to gather as much data as possible about the surveyed surfaces. Our goal — to elaborate a good operative protocol to survey large-scale archaeological complexes — significantly impacted on our choice of methods and techniques (Docci *et al.*, 2011; Green *et al.*, 2014; Cipriani and Fantini, 2015; Gaiani, 2015). Although these theatres were all the same type and were used for the same purposes, they differed in their metric and geometric characteristics, discontinuities, materials, colours and state of conservation. These choices were further influenced by the fact that we would later have to elaborate 2D and 3D models with similar and therefore comparable characteristics. Establishing an acquisition process that could be repeated for the six case studies inspired us to obtain homogeneous models based on the same amount of data and representation type.

By integrating non-contact survey methods, we were able to jointly use topographic instruments, 3D laser scanners and photographs (Chiabrando *et al.*, 2010). Before initiating the project we established the criteria and way in which we would use these instruments; topography was entrusted with the management and control of the uncertainty[10] of such a large-scale survey. We prepared a topographic polygonal that was either open or closed according to the requirements imposed by the surroundings; this allowed us to not only place each theatre in a rigidly-controlled grid, but also measure several important points selected directly on the object. In addition, we were then able to register the points clouds obtained with the 3D laser scanner in a single Cartesian reference system. In all the case studies we tried to make the position of the topographic stations coincide with the positions of the scanner; our objective was to obtain homogeneous numerical models so that we could make comparisons.

We decided to execute not only general scans (1 × 1 cm sample spacing) of all the sites to gather data regarding the size, morphology and shape of the archaeological complexes, but also detailed scans (2 × 2 mm sample spacing) for particularly important architectural/archaeological elements.

The drawing scale of the two–dimensional models was chosen in order to provide representations that could be useful in the study of archaeological artefacts[11]: 1:200 for geometric drawings, 1:100 for architectural drawings of the whole complex, and 1:50 for representations of details.

Since the points clouds were difficult to manage due to the size and density of the acquired points, they were suitably processed[12] to eliminate redundancies and establish data that could be useful later on. This was the last operation in the data acquisition phase; we monitored the registration error so as to maintain it below values in line with the uncertainty of the 3D scanner (≤ 4 mm) and with the scale of the drawings.

Data processing

Data processing is a complex phase, closely linked to what it is the scholar intends to communicate vis-à-vis the analysed object.

When archaeological issues are involved we have to consider how we want to document, communicate and disseminate the information in a sector in which, compared to others, the use of digital models has taken longer to become routine.

Creating 2D and 3D models makes it possible to shift from a real object to its representation by selecting some of the endless data concerning the object (Ippolito, 2007). Obviously, the more the virtual data corresponds to the real object, the more accurate the analysis and interpretation (Koutsoudis *et al.*, 2014).

Two issues have to be tackled when the moment comes to build models and drawings of extremely irregular

[9] This statement does not wish to imply that acquiring a massive amount of data is a completely automatic process performed without filtering by the operator. Laser scansion requires an initial choice to be made regarding the restitution scale of the drawings, because the specific definition of the values associated with certain parameters is linked to this objective. During photomodelling the following have to be taken into consideration: the number of shots, the quality and homogeneity of the photographs vis-à-vis accessibility and lighting conditions, the type of photographic reading pattern based on the morphology and geometry of the object, and the level of detail of the intended model.

[10] The instrumental uncertainty for the Leica Geosystem TPS800 total station is equal to a tenth of a millimetre.

[11] A geometric diagram tends towards geometrisation of the elements to be represented, explicitly indicating the morphology and spatiality of the artefact. An architectural diagram shows the real configuration of the elements and provides graphic characterisation, indicating the quality of the surfaces or their state of conservation.

[12] *Cloudworx*, the Leica Geosystem application.

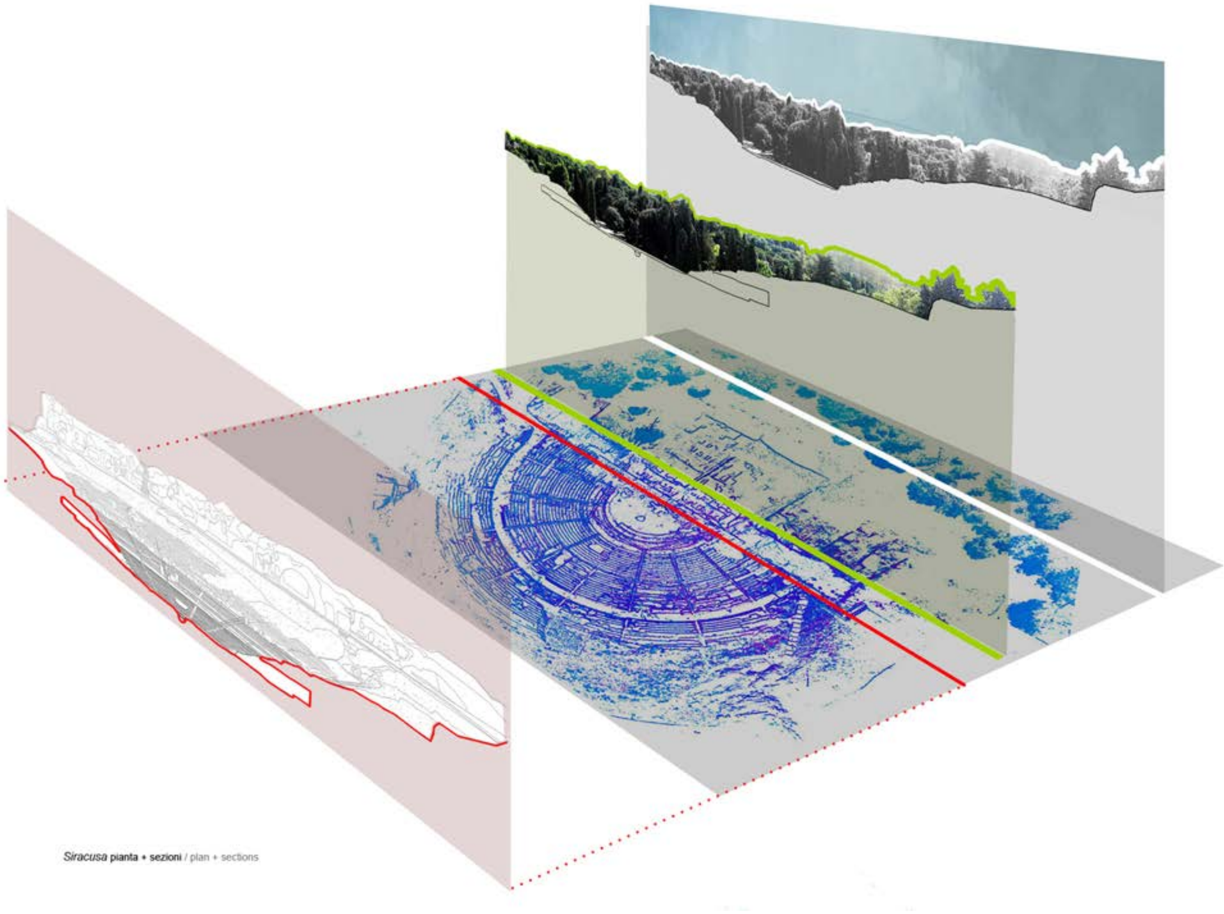

Figure 2. The relevance of different data formats: raw point cloud, RGB texturization, reflectance level texturization.

artefacts such as the theatres in this study. The first involves the need to understand and underscore the unique aspects of these contexts — large, sprawling areas and geometrically irregular archaeological artefacts — since the latter effectively stop the researcher from identifying sharp edges or precise forms. The second issue involves the representation scale, in the case of 2D models, and the level of detail for 3D models (Borgogni and Ippolito, 2011).

Multilevel analytical documentation, represented by unprocessed data, is an important aspect when defining 2D / 3D models. It includes absolutely free documentation for all scholars; 3D models that can reach a 1:1 scale with the possibility to use texture mapping to characterise surfaces; the *publisher* programme allowing anyone to visualise and explore (even online) high-definition panoramic images of the points cloud illustrating the positions of the scanner during acquisition and providing the possibility to extract the coordinates of the selected points as well as measure distances (Gaiani *et al*., 2011).

The process used to define the general and detailed 3D models is divided into separate phases that follow on from the registration of the point cloud and allow accurate determination of the topology of the surfaces (Bulbul *et al*., 2011; Bourke, 2012).

These models, whether geometric, texturized or thematic, were the basis for a series of considerations about the form of the surfaces, their regularity/irregularity, their state of conservation, and the analysis of the materials (Lo Brutto and Meli, 2012).

Furthermore, depending on the type of model and its characteristics, it is possible to communicate different aspects of the objects considered (Figure 2).

For example, even if the geometric model has no chromatic or material data (Figure 3) it is still very useful to study the arrangement of masses, geometry and proportions as well as to understand the reciprocal position and relationship between the elements in the architectural composition.

Instead, the texturized model helps to define the formal aspects and state of conservation of the artefact by first of all using the RGB data (Figure 4) obtained from the digital images acquired by the same instrument

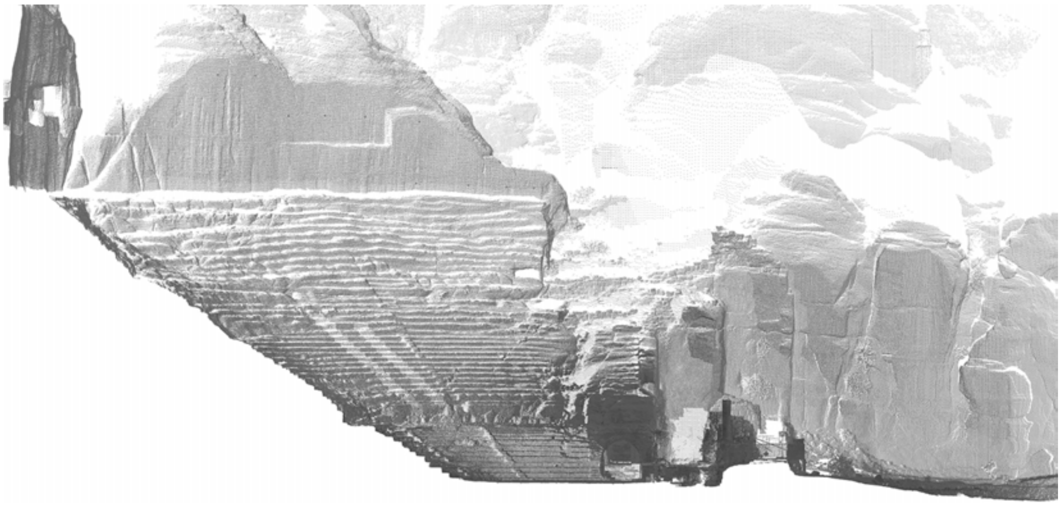

Figure 3. Petra Theatre, transversal section (raw point cloud).

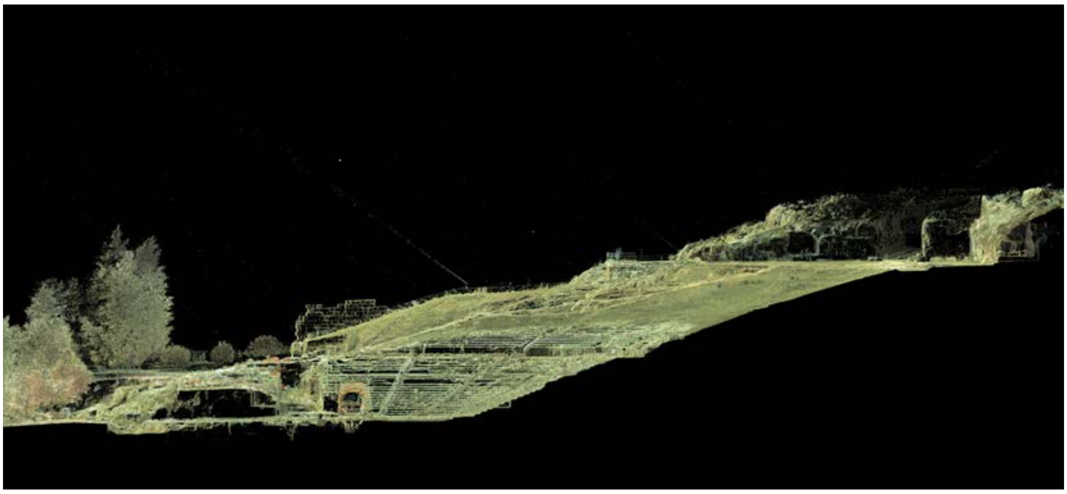

Figure 4. Siracusa Theatre, transversal section, RGB texturization.

at the same time as the scans: the chromatic data in these images is very accurately linked to the geometric position of any surveyed points.

Finally, the thematic model exploits the symbolic nature of colour to provide information about several different aspects. By using colour to establish homogeneous areas in the model we can highlight forms, the heterogeneity of the materials, their state of conservation and sometimes even their degradation pathologies (Figure 5).

The irregularity and distinctive traits of the artefacts in this study made it necessary to document their morphology based on a plan which, during acquisition and re-drawing, ranged from the general to details. As a result, we were able to produce traditional geometric and architectural representations.

It's very important to understand the 'contact point' between products created by traditional survey activities and those generated by new massive acquisition technologies. It involves not only the operational aspects associated with the production of the drawings, but the more general issue of how cognitive processes work in the world at large.

We made general models and in–depth detailed models for each theatre in order to provide materials that could be useful in different kinds of analyses and interpretations ranging from the compositional geometric aspect to the study of the quality of the

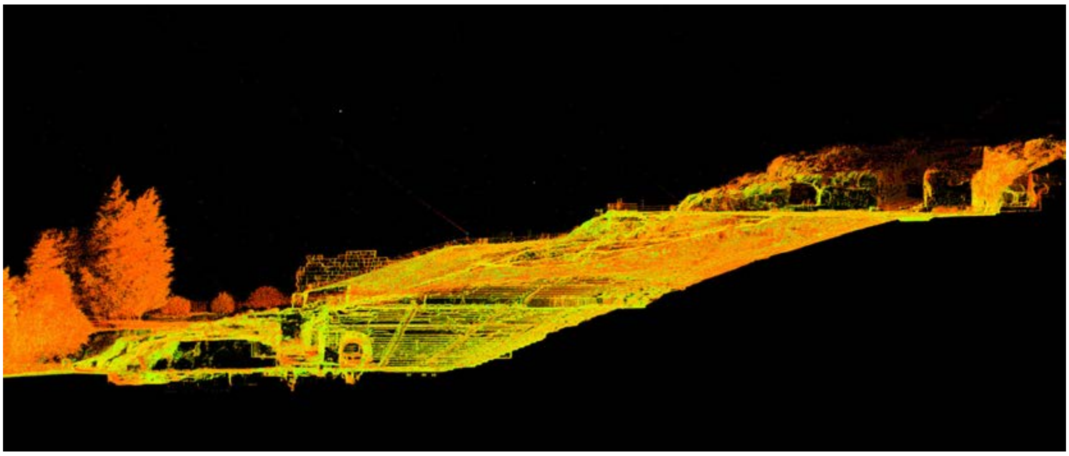

Figure 5. Siracusa Theatre, transversal section, reflectance level texturization.

surfaces. The following list shows the contents of the two–dimensional drawings executed for the six case studies in this research (Figures 6, 7, 8 and 9).

- geometric models:
    plan, scale 1:200
    transversal section, scale 1:200
    longitudinal section, scale 1:200

- architectural models:
    plan, scale 1:100
    transversal section, scale 1:100
    longitudinal section, scale 1:100.

Choosing which drawings to produce depends on the objective to provide the most comprehensive cognitive picture of the six theatres. The drawings show the relationships between the structure and its context, morphology and sequence of elements: the cavea, the *scaenae frons* and the *tribunalia* (where present), etc. (Figure 10).

Another important aspect was the possibility to visualise, explore and export images of the cloud in which some points are recoloured from blue to red depending on reflectance values. In fact, chromatic differences allow a point-by-point interpretation of the material characteristics of the analysed objects. Users can elaborate this data either to acquire better knowledge during processing, or to provide a more comprehensive communication. Representation of the point cloud in false colours produced reflectance ranges that vary depending on the material, but also on the state of conservation within homogeneous areas.

A correct approach to developing archaeological or architectural models must first solve the following issues before research can start: redefining the concept of the scale of digital models now geometrically and perceptively separate from a paper support; the quality and scientific nature of the data vis-à-vis uncertainty; and aspects associated with dissemination, exchange and fruition of heterogeneous data.

Data analysis

Generally speaking, activities aimed at gathering *in–depth information* about artefacts can only be considered complete if they provide new content. In fact, data acquisition and processing does not end with the creation of 2D and 3D models, but rather with the drafting of hypotheses based on the interpretation of those models. Furthermore, an overall vision of the object in question is not achieved only by creating 2D drawings or 3D models.

The aim of our study was to scientifically interpret the six archaeological complexes. To achieve our goal we used a consolidated method allowing us to not only examine each theatre individually, but also compare them based on what they had in common.

The numerical models and relative 2D geometric drawings of the theatres in Mérida, Petra, Jerash, Carthage, Siracusa, and Cherchell were used as the basis of a series of studies to gather more knowledge and get a better understanding of their formal matrix (Marta, 1990; Morachiello, 2009). The studies were based on a preparatory geometric analysis of the elements behind the creation of their architectural space, as well as on a study of their form conducted primarily on 2D models.

We checked the geometry and dimensions of the layouts of the theatres based on the essays of two important treatise writers both involved with theatrical buildings, albeit each in his own way: the

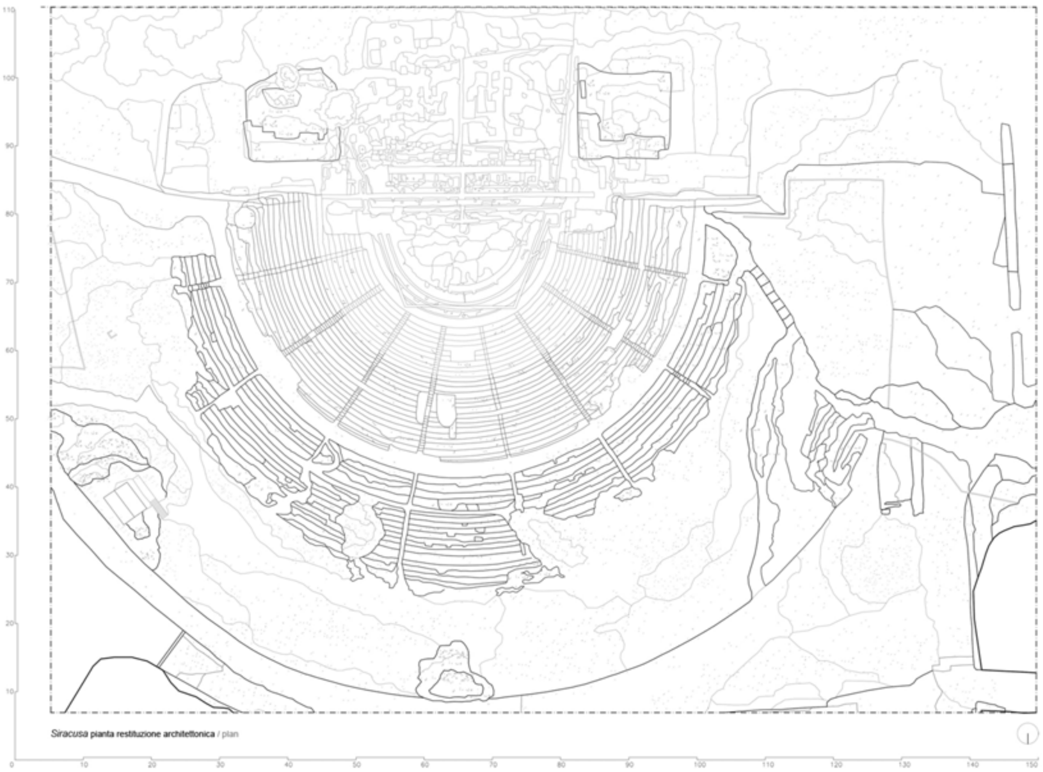

Figure 6. Siracusa Theatre, plan view, architectural line drawing.

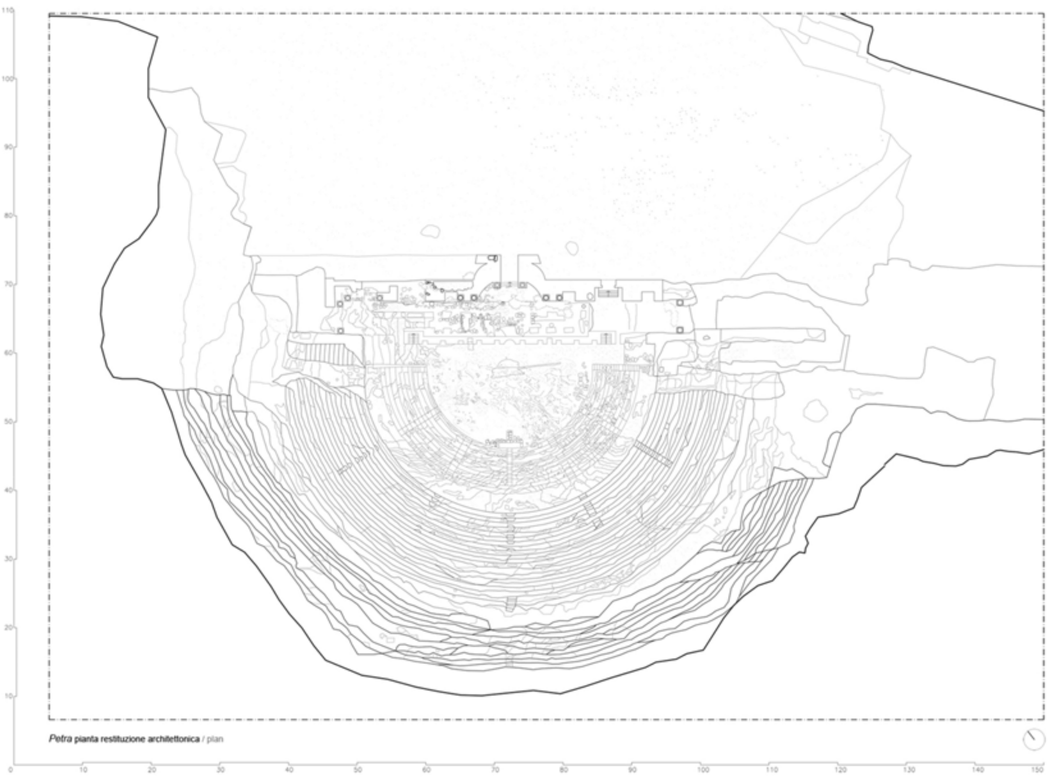

Figure 7. Petra Theatre, plan view, architectural line drawing.

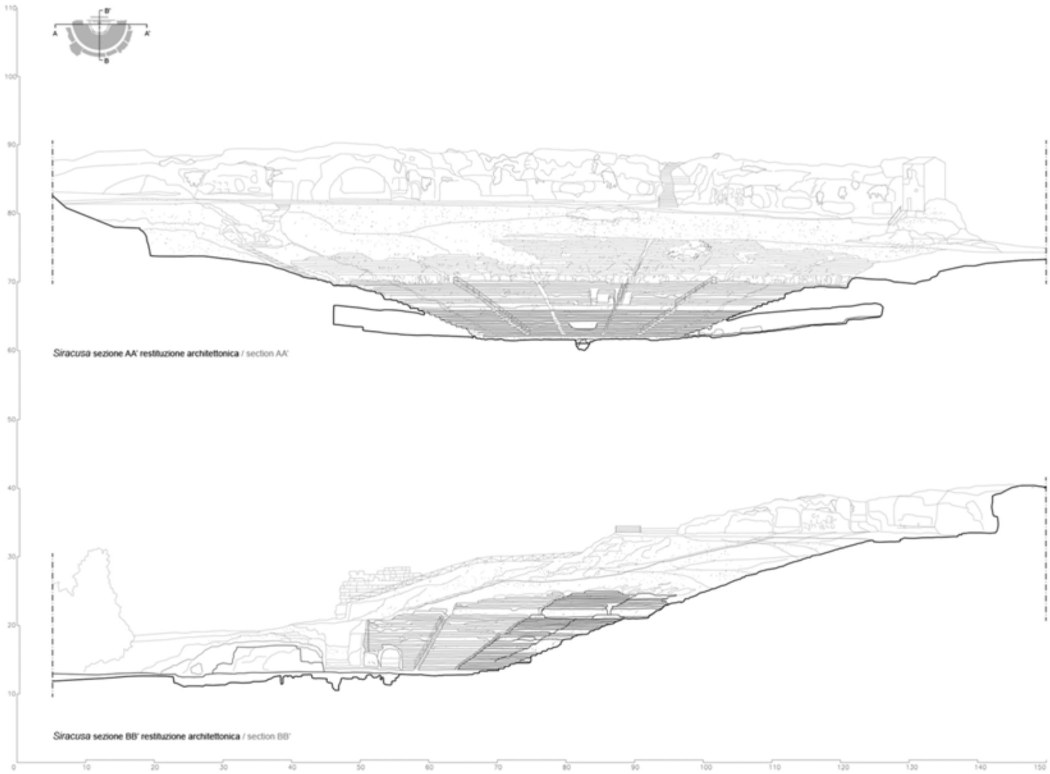

Figure 8. Siracusa Theatre, transversal and longitudinal sections, architectural line drawing.

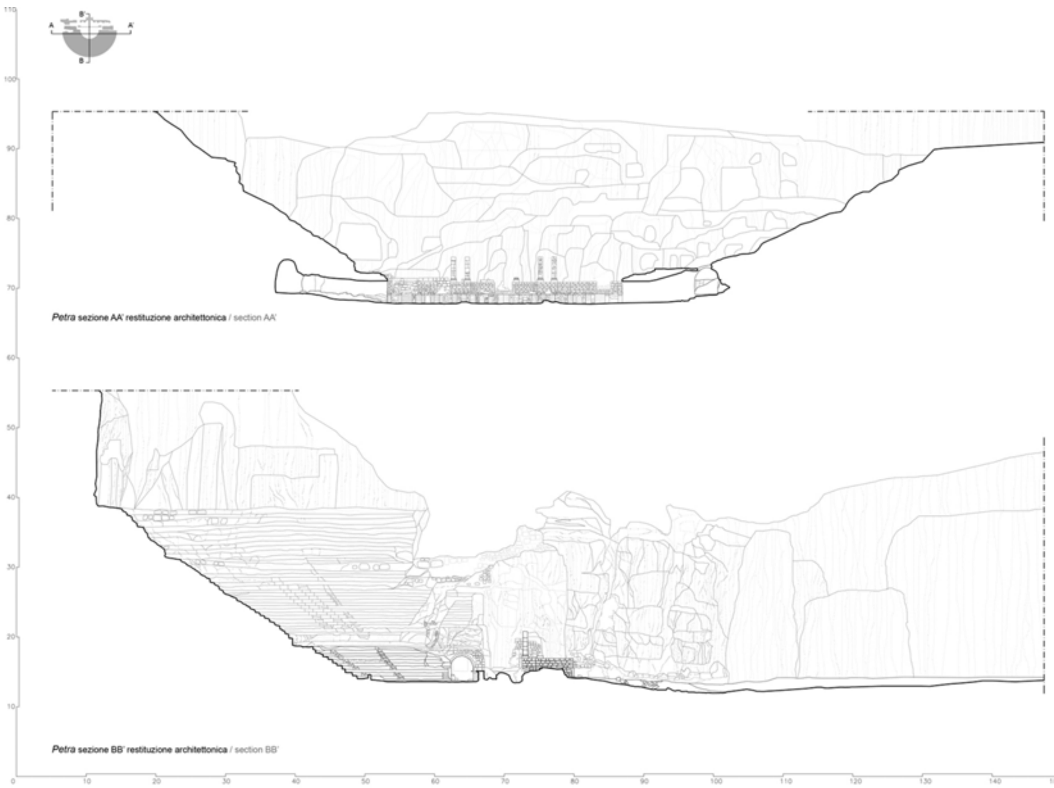

Figure 9. Petra Theatre, transversal and longitudinal sections, architectural line drawing.

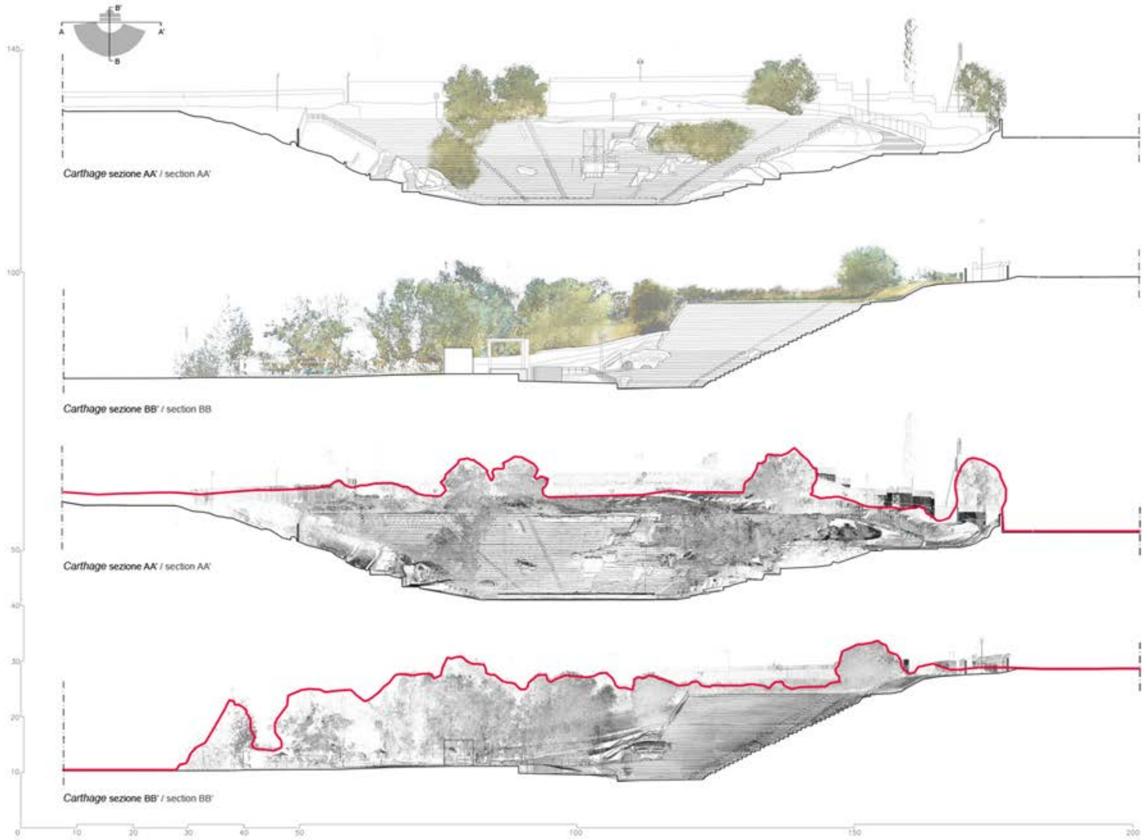

Figure10. Carthage Theatre, transversal and longitudinal sections, contextual representations.

De Mensuris and Stereometrica by the mathematician Heron of Alexandria (first, second or third century AD) and De Architectura by the Latin architect Marcus Vitruvius Pollio (1st century BC). Heron elaborated several formula to calculate the seating capacity of entertainment buildings based on their size, i.e., the *loca* of the number of spectators. Vitruvius, instead, used a series of geometric constructions to establish the main proportions between parts of the theatre (Figures 11 and 12) (Gros, 1997). They both elaborated formulas and geometric schema to assist contemporary designers; in this study we used these formulas and schema to verify the theatres, their component parts and the geometries behind their size and design (Gros, 2001; Salvatore, 2007).

We used a popular study method — combining geometric analysis and measurement analysis — to discover whether or not a metric matrix or reference module had been used (Centofanti, 2008). We then performed several metric and proportional tests on the main elements of the theatres considered as a construction type: the cavea, orchestra and theatre stage. Since the theatres were either built or restored by the Romans, our base module was the Roman *pes* (with a value of 0.296 m) and its multiples, such as the *pertica* (equal to 10 pedes). Our first test was performed to see whether this module could be applied to the whole theatre.

Metrological analysis

Verification was performed for the theatres in Petra, Jerash and Mérida considering that the state of conservation of the theatres in Carthage, Siracusa and Cherchell did not allow us to determine the values needed for this procedure. As mentioned above, we took as our base module the Roman *pes* (with a value of 0.296 m) and its multiples. The metrological analysis was performed on the main elements of the theatres: the diameter of the orchestra, the diameter of the cavea (adding together the summa, media and ima cavea) and the length of the theatre stage (Figure 13).

Petra
Diameter of the orchestra 120 pedes (35.523 m)
Radius of the cavea 98 pedes (29.00 m)
Length of the theatre stage 81 pedes (23.97 m)

Jerash
Diameter of the orchestra 68 pedes (20.12 m)
Radius of the cavea 98 pedes (29.00 m)
Length of the theatre stage 122 pedes (36.11 m)

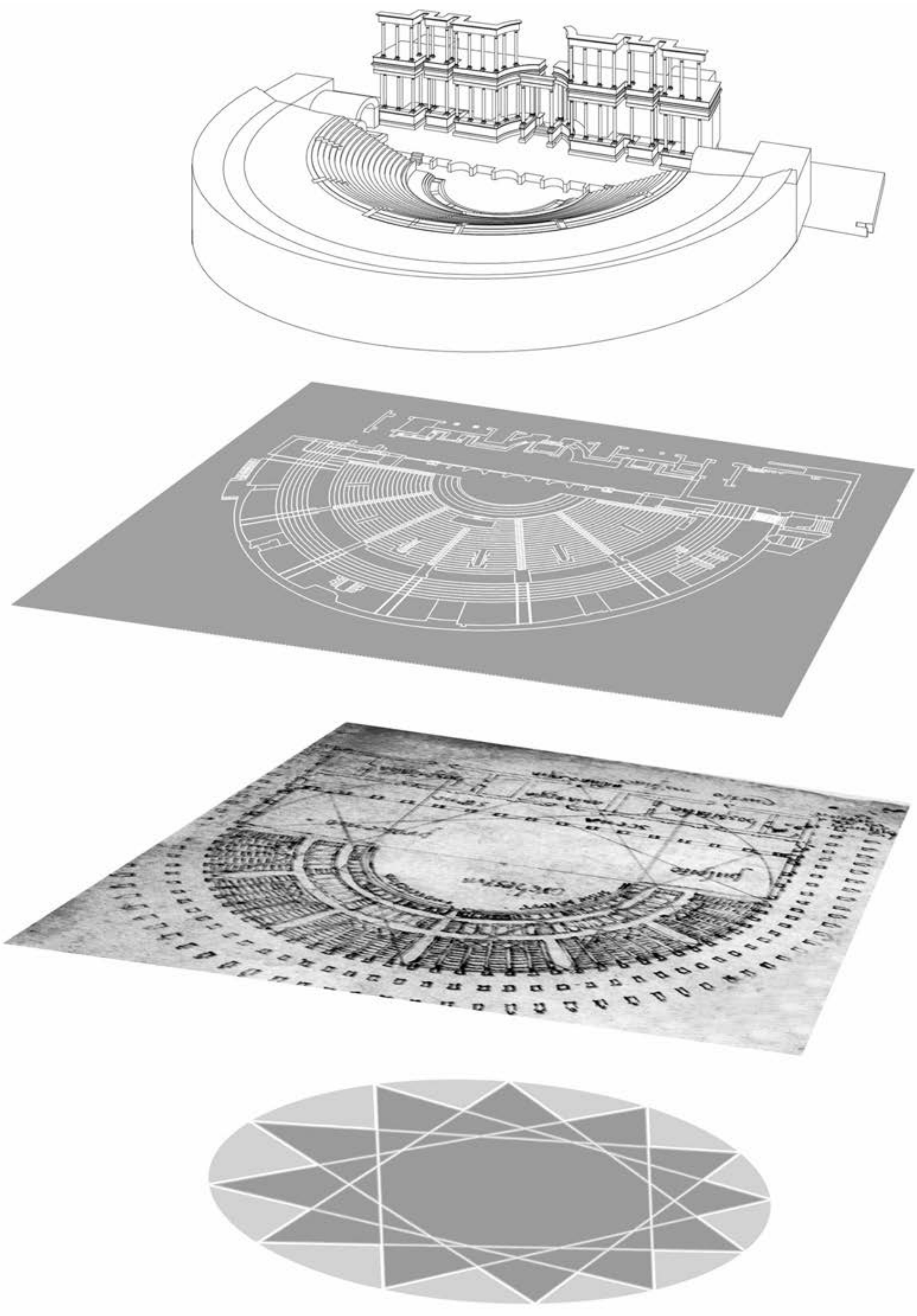

Figure 11. The Vitruvio's Rule.

Mérida
Diameter of the orchestra 61 pedes (18.00 m)
Radius of the cavea 150 pedes (44.40 m)
Length of the theatre stage 177 pedes (52.39 m)

Comparative analysis: Heron's theory

In this study we made a comparison between Heron's theory and several theatres. We used a previous study of the theatres (Bianchini and Fantini, 2015) in Petra, Jerash and Mérida considering that the state of conservation of the other theatres in Carthage, Siracusa and Cherchell did not allow us to determine the values of the cavea needed for verification. Verification was performed using *De Mensuris* 24 and paragraph 42 of *Stereometrica* (40–43) entitled 'Different ways to calculate the *catini*', Heron provides other examples of how to calculate the seating capacity of a theatre.

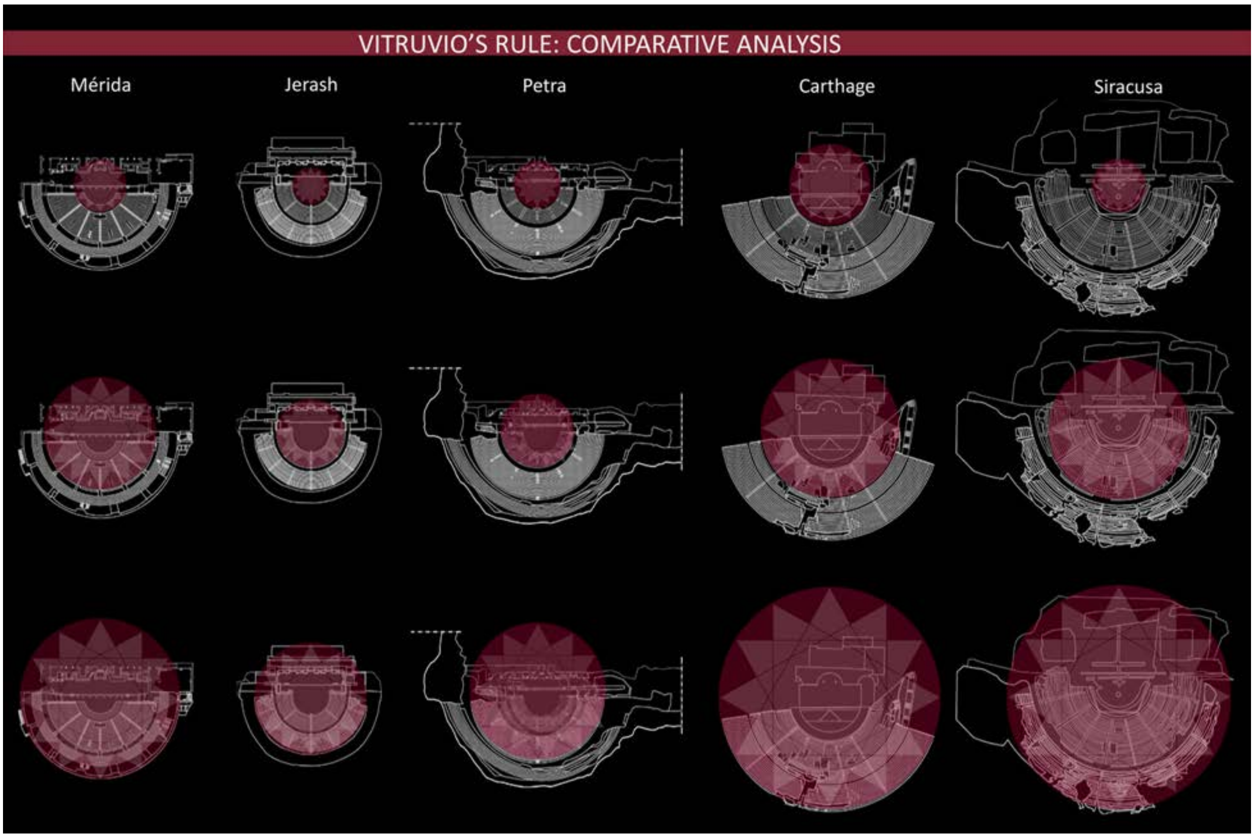

Figure 12. The Vitruvio's Rule, comparative analysis.

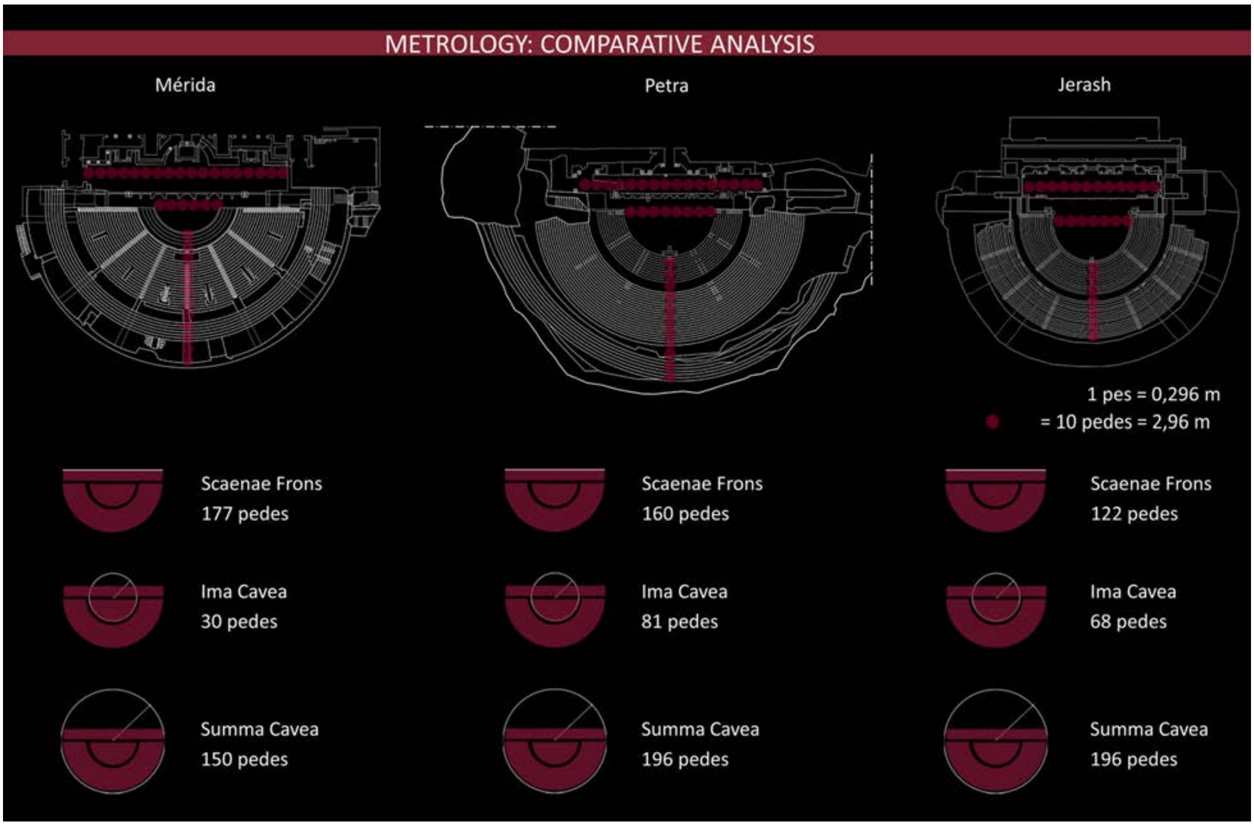

Figure 13. Metrological analysis for the theatres of Mérida, Petra and Jerash.

Mérida
According to Heron's rule, the intermediate semicircumference is (421 + 124) / 2 = 268 *pedes*. The *analemmata* is 52 *pedes*. The width of the seats is 2.5 *pedes*, so the theoretical number of rows is 21 and the number of spectators is therefore 268 × 21 = 5,681 *loca.*

Petra
According to Heron's rule, the intermediate semicircumference is (359 + 130) / 2 = 244 *pedes*. The *analemmata* is 79 *pedes*. The width of the seats is 2.3 *pedes*, therefore: 79 / 2.3 = 34 rows, and the number of spectators: 244 × 34 = 8,380 *loca*.

Jerash
According to Heron's rule, the intermediate semicircumference is (317 + 107) / 2 = 139 *pedes*. The *analemmata* is made up of 8 modules of 8 *pedes* (64 *pedes*). The width of the seats is 2 pedes, therefore the theoretical number of rows is 32; and the number of spectators 212 × 32 = 6,748 *loca*.

Conclusion

To understand and interpret the theatres we chiefly used 2D and 3D drawings highlighting the unique features and geometric, morphological and spatial characteristics of each theatre.

Accordingly, geometric drawings, architectural drawings and thematic models, characterised by the restitution of different kinds of appropriately selected data, are very successful. In fact, often the selective, specialised interpretation of several features of an artefact can provide a comprehensive cognitive picture of the analysed objects. Different integrated representation techniques were used to construct the models: rapid sketches capturing first impressions based on features immediately obvious from an initial contact with reality; well thought-out drawings based on a more accurate representation highlighting the current state of an artefact; photographs and numerical models providing basically objective data. In particular, establishing this data depends on an informed use of massive acquisition instruments and techniques. For example, reflectance data or the RGB datum of the chromatic component of the points cloud enables a series of specific analyses to be performed on aspects and characteristics of material surfaces that are not immediately perceptible. Integrating and processing this kind of information, based on objective data and traditionally expressed in an exclusively digital environment, makes it possible to propose new models that help to appreciate *other* significant aspects of the object.

However, IT devices do have much greater potential due to the continuous technological progress made in the field of survey and everything associated with the restitution of drawings. Firstly, digital graphic models can be represented within vast virtual space without a reduction of scale vis-à-vis reality; secondly, they are not bound to any specific, previously-chosen representation method (perspective, axonometric projection, orthogonal projection, etc.), but reacquire real three-dimensionality inside the computer that provides several simultaneous, real–time visualisations of the same object.

A correct approach to developing archaeological or architectural models must first solve the following issues before research can start: redefining the concept of the scale of digital models now geometrically and perceptively separate from a paper support; the quality and scientific nature of the data vis-à-vis uncertainty; and aspects associated with dissemination, exchange and fruition of heterogeneous data.

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Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
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Archaeology and Augmented Reality. Visualizing Stone Age Sea Level on Location

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Abstract

When interpreting and disseminating the localisation of Stone Age sites along the rugged coast of Norway, it is always pertinent to include knowledge about sea level at the time the various sites were in use. This is important for archaeological surveying and excavation, as well as mediation to the public at large. When one finds oneself on a Stone Age site a kilometre inland and in the thick of a dark forest, it is not easy to imagine what the place actually looked like six thousand years earlier when the site was in use by Neolithic people, and was part of a coastline exposed to the open sea. How can we take advantage of the current state-of-the-art in location-based media and mobile augmented reality in order to bring dynamic visualizations of the ancient landscape into the hands of both archaeologists and interested visitors? In this article, we report on the development and testing of a situated simulation where the user can move around in a given landscape and view a parallel simulation of the sea level from pre-historic times up to the present on a smartphone or tablet. The application uses an indirect augmented reality solution and the sea level/time-period can be altered continuously. When approaching a surveyed and/or excavated site, one can also observe its extent and via spatially positioned hypertext links, access the online databases for multimodal information about the findings. The prototype runs on iOS and has been tested with a small group of visitors on location. The article concludes with a discussion of the user evaluation and suggestions for further work.

Keywords: visualisation, situated simulation, mobile augmented reality, land rise, Norway

Introduction

Anyone familiar with archaeology in the field knows how challenging it might be to imagine how a particular location may have appeared in prehistoric times, in particular given changes in vegetation and sea level. This may not be insurmountable for the individual surveyor searching for relics or traces of ancient and historical culture; with experience the field archaeologists will cultivate adequate judgemental powers in order to distinguish the look of the present surrounding from its many past variations. However, for the untrained eye of the layperson, such changes may be very difficult and challenging to comprehend. How may we employ recent developments in mobile digital technology to solve some of the visualizing challenges in these on site situations? Mobile augmented reality solutions have, for quite some time, been developed for use on cultural heritage sites (Vlahakis *et al*., 2000; Tscheu and Buhallis, 2016) and suggested and tested for various aspects related to archaeological fieldwork (Mohammed-Amin *et al*., 2012; Deliyiannis and Papaioannou, 2014; Liestøl and Rasmussen, 2010). However, such systems have primarily been focused on the archaeological reconstructions rather than the surrounding area, such as the larger natural environment including change in sea level and vegetation.

In the project reported here, we have deployed a platform for publishing situated simulations, a kind of Indirect Augmented Reality (Wither *et al*., 2011), which has been in development since 2008, and applied to a variety of cultural heritage sites as well as simulations representing climate change (Liestøl *et al*., 2014). In a situated simulation (sitsim) the user's visual perception of the real physical environment is coupled with the user's visual perception of a 3D graphics environment as displayed on a hand-held screen. The relative congruity between the real and the virtual perspectives is obtained by letting the camera position and movement in the 3D environment be conditioned by the positioning, movement and orientation hardware. As the user moves in real space, the perspective inside the 3D graphic environment changes accordingly in

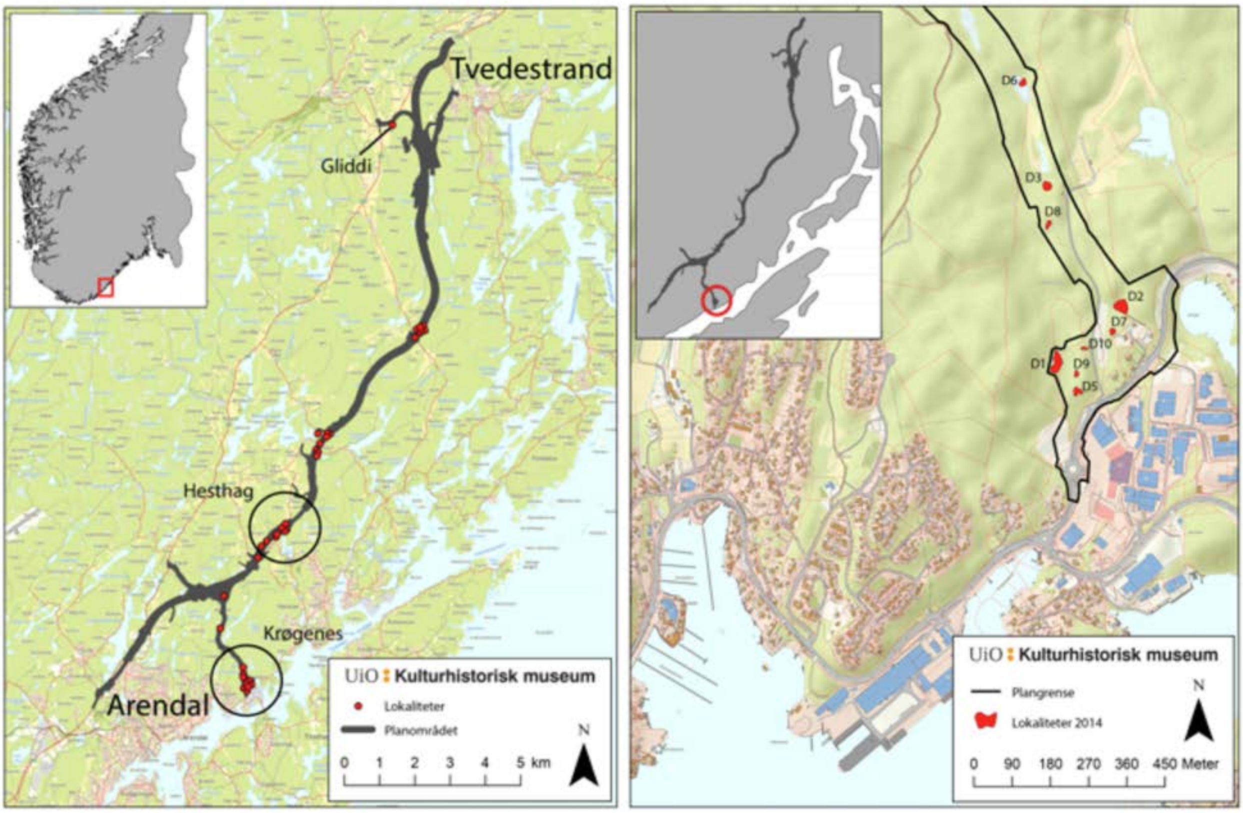

Figure 1. Location of the Krøgenes sites.

real time. The system also includes spatially distributed hypertext links for access to various kinds of additional information and different 'views' (zoom, bird's view etc.) for improved orientation and observation (Liestøl and Morrison, 2013), for more information see the projects web site at www.sitsim.no.

The main purpose of the experiment reported here was to create a dynamic, digital 3D environment for continuous display of changes in sea level and vegetation. At the same time, it includes the location of the excavated Stone Age sites in the area and allows access to the online archaeological databases of findings based on the excavations. In the following we first describe the archaeological area in question and the excavations; then we present the digital field museum and its databases, which can be accessed on location. Further, we describe the programming architecture as well as the graphical solutions, before finally presenting the test and evaluation with a small group of users on location. We conclude with some suggestions for further work.

The Krøgenes sites and excavations

On the southern–most coastline of Norway, between Tvedestrand and Arendal, 38 archaeological sites were excavated in the period 2014–2016 due to the building of the new E-18 motorway in the area. The new road is about 2–3 km from the present coastline, and the landscape is hilly with small fjords.

In the Stone Age, the landscape was rather different, with higher sea levels than today due to the isostatic land rise after the Ice Age. Based on the landscape formations, the archaeological localities are interpreted as coast-bound sites. Consequently, the oldest are situated highest in the landscape, and the youngest further down. The Stone Age people lived predominantly very close to the sea. The area chosen for the sitsim presented here is called *Krøgenes*. It is located on the north–western side of Tromøy and the city of Arendal. Nine settlements were excavated here in 2014. These sites are located from 14–58 m a.s.l., dating from the Middle Mesolithic to the Middle Neolithic periods. There are also several quartz quarries in the area, which have been in use from the Stone Age up to modern times.

The area as a whole may have looked quite similar in the Stone Age, as the landscape appears today, with small fjords, archipelagos and small islands providing good protection from the open sea. This is one of the main reasons for choosing it for modelling a prehistoric landscape, together with archaeological results based on excavated localities placed at different sea

Figure 2. Krøgenes D2-

Figure 3. Krøgenes D7 and Krøgenes D10.

levels. The different heights of settlements in a small area like this also provides a unique potential to see connections, similarities and differences between them as the sea level and vegetation change over time. In the sitsim, three different settlements were chosen as representative for the Krøgenes area:

Krøgenes D2 (22 m a.s.l.) showed a massive cultural layer, and axe production. The settlement is situated in a natural amphi, and is dated to the Late Mesolithic period. The site has around 23,000 finds of flint, quartz and local stone used for the axe production.

Krøgenes D7 (19 m a.s.l.) is a small single-phase settlement from the Early Neolithic period. The majority of the finds are flint debitage from the reduction of flint cores.

Krøgenes D10 (19 m a.s.l.) is located opposite D7 on the other side of a prehistoric inlet, and also from the Early Neolithic. The finds were quite similar, except from a small area with 4200 pieces of processed quartz, which probably represents a single event at the site.

Connecting to the *Digital Field Museum*

The sitsim was developed as part of the *Digital Field Museum* project. Excavations always create interest locally, but too often an excavation and the subsequent curating of the finds are separate events. *Digital Field Museum* was started to bring excavations and museum collections closer and to create more understanding of the links between the knowledge of prehistory, the exhibitions and the excavations. This will be achieved by bringing the collections out to the excavation site and the excavations into the museum. In 2015, two parts of this project were carried out. One was an event at the museum where school classes were online with one of the E18 excavation sites. The archaeologists in Tvedestrand used mobile devices to guide around the excavation site and to answer questions, and the students were quite enthusiastic about being online and communicating with the archaeologists. The other task in 2015 was to develop the sitsim-application presented here, which would increase the understanding of the paleo-environment at the site and also be a starting point for an investigation of the collections and documentation at the Museum of Cultural History at the University of Oslo.

The Museum of Cultural History is responsible for all prehistoric excavations in the ten eastern and southern most counties in Norway. The excavation documentation is now born digital, and earlier catalogues and photo documentation have been digitised. As a result, the collections are available online, and all new acquisitions are catalogued in the national database systems for the university museums and published at www.unimus.no. All of the archaeological collections at the university museums in Norway use the same net portal, and as of August 2016, close to one million entries are published. The artefact catalogues are geotagged and this and other metadata can be freely downloaded. Photographs from excavations and of artefacts are published with CC—licence (Matsumoto and Uleberg, 2015). Excavation reports are now published at http://www.duo.uio.no, which is the Open Research Archive at the University of Oslo. So far more than 100 excavation reports have been published. All in all, there are large amounts of data waiting to be used in different applications.

Programming challenges and architecture

With the release of the iPhone in 2007 and the iPhone SDK in 2008, mobile computing became reality. The development of sitsim-applications started in the fall of 2008 and has since the start primarily been based on the iOS platform and Unity game engine. With a game engine supporting multiple platforms, some applications have also been adapted to the Android platform. Over the years, technical advancements in mobile devices have resulted in better performance, graphics capabilities, and new and more accurate sensors. Although the applications have been developed continuously and benefit hugely from these advancements, there are still challenges, mainly regarding the limited performance of mobile devices. Because of these limitations, there will always be a need for simplifications, in models, graphics, accuracy etc. These simplifications have to be carefully weighted and implemented with each individual application in order to not affect their main purposes and key values.

With a sitsim application being a kind of augmented reality application, the user is moving around and pointing the device in different directions instead of using ordinary game controllers with sticks and buttons to control the perspective. One can see the device as a window into the past (or the future) instead of the current reality, and exploring the application is as simple as using a point-and-shoot camera. Sitsim applications usually cover a very large area (often more than 10,000s of square meters) and the use of visual (fiducial) markers (which is nearly standard in most mixed and augmented reality applications) is impossible. Instead, the application is relying on the device's own sensors only when aligning the perspective of the simulated 3D graphics environment with that of the physical reality. The GPS is used to acquire the user's position, down to an accuracy of three meters,

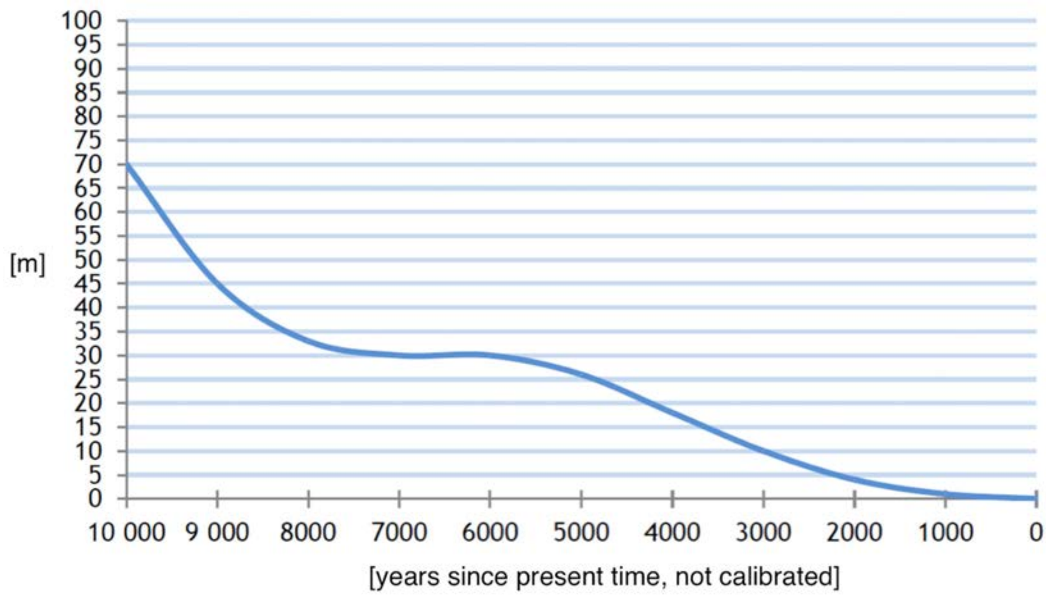

Figure 4. Changes in sea level over time (after Andersen, 1976).

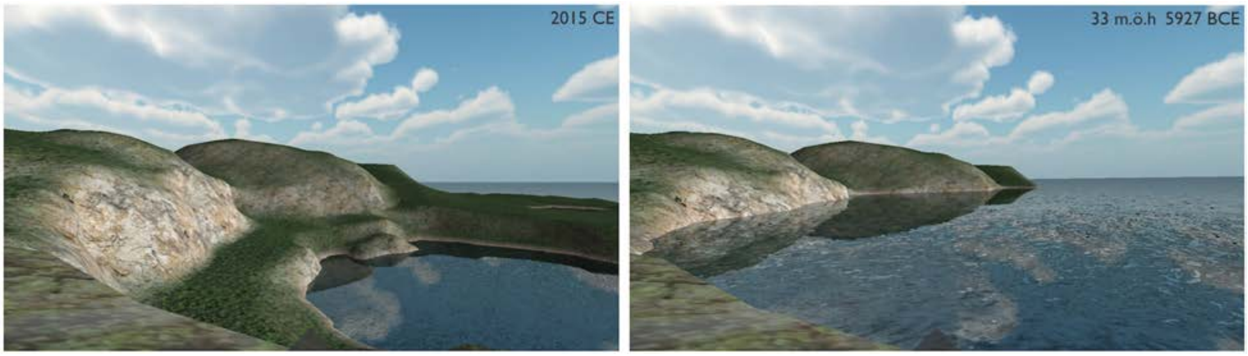

Figure 5. Changes in sea level: 2015 AD versus 5927 BC (screenshot from the Krøgenes prototype).

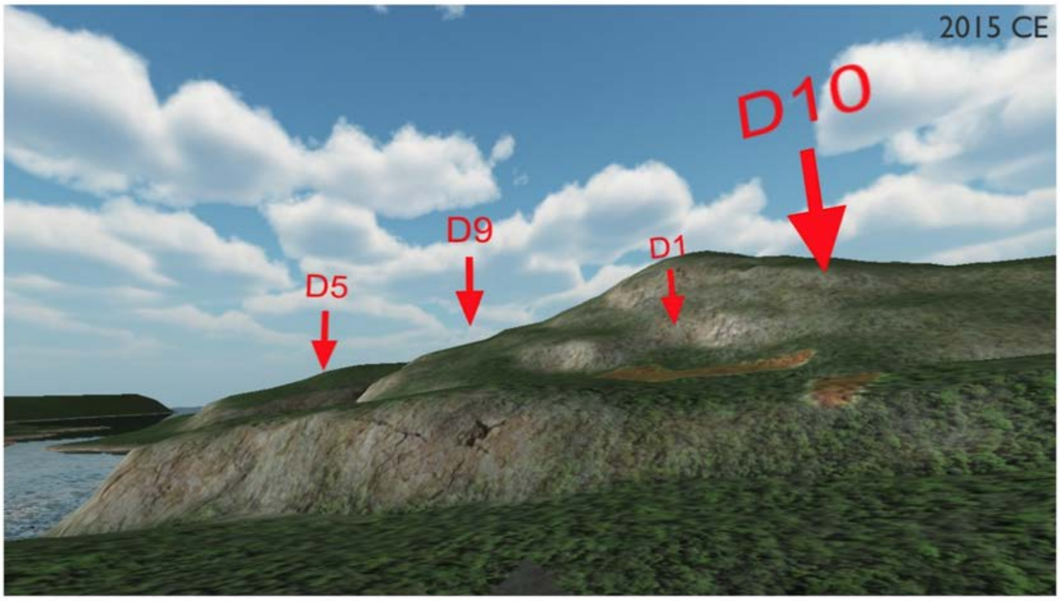

Figure 6. Marking the stonage sites in the terrain.

depending on the surroundings and current weather. In order to track the device's orientation, both in short term (fast rotations in fractions of a second) and long term (stay calibrated over time), the output from the compass, accelerometer and gyroscope is fed through a calibrated filter to calculate the orientation of the artificial camera in the application. The only tools used to create the sitsim application (excluding tools used for graphical content such as 3D models and textures) are Unity (user facing functionality and 3D graphics visualisation) and Xcode (access to sensors and other device specific functionality).

The ambition of this project has not been to create a photorealistic representation of the actual sites, but to capture the changes of the shore line with post-glacial rebound and how that maps with known settlements in the area of interest.

The prototype is modelled on two basic assumptions regarding the area: a) it's mainly covered with a homogenous vegetation, regardless of altitude and timeframe; b) the post-glacial rebound is uniform and the elevation profile is unaffected over time. In order to achieve a more visually realistic and appealing presentation, the vegetation is also assumed to be sparse in steep terrain and close to the shoreline.

For technical simplicity, only three different vegetation/ terrain types were used to visualize the terrain: a) Forest: Dense forest with medium sized trees and large bushes; b) Grass, moss and lichen: Rock partly covered with grass, moss and lichen; and c) Rock: Bare rock. The vegetation types were visually presented by applying different alpha textures to the terrain, no 3D-models of trees or shrubs are used in the current prototype.

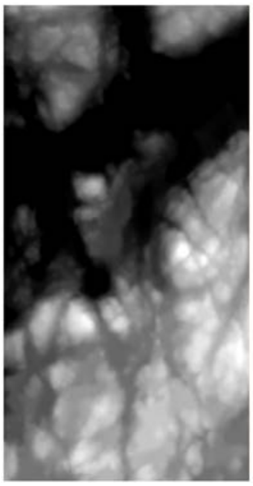

Figure 7. Height map.

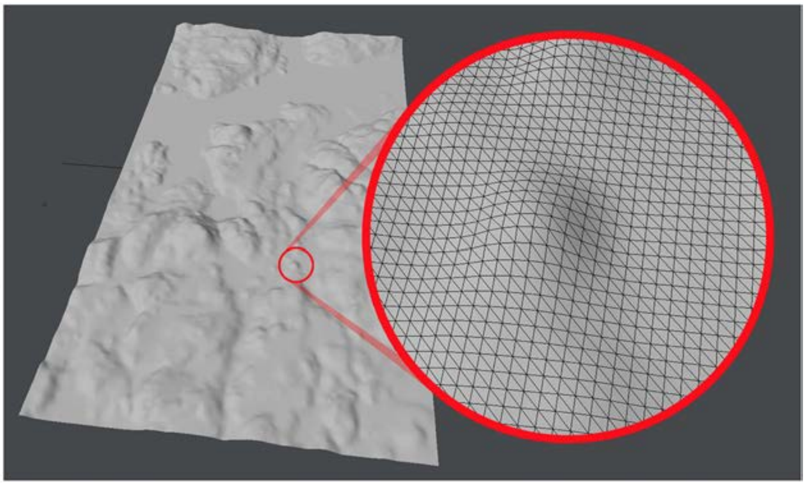

Figure 8. The resulting 3D mesh.

The altitude above sea level and the inclination of the terrain are used as input values when calculating the visibility of each vegetation type. The final result is achieved by calculating the resulting terrain texture in two steps: 1) starting at sea level and moving upwards, grass, moss and lichen gradually changes from full visibility to transparency at the same time as forest changes from full transparency to visibility; 2) the visibility of the result from the previous calculation is modified depending on the slope-in vertical terrain it is fully transparent and only rock is visible, as the terrain gets less steep it gradually gets more visible and finally covers the rock completely.

In the prototype, the user can control the timeframe using a slider ranging from 8300 BCE to present time. The modelled rebound is based on Andersen (1976), see Figure 4. For simplicity of implementation, the sea level is increased as the user moves the slider back in time, instead of lowering the terrain into the sea, the visual appearance and end result is the same. Figure 5 above illustrates the difference in sea level (actually rebound); the sea level around 6000 BCE was approximately 33 m higher than it is today.

To help the user find the interesting settlements, it is possible to activate a highlighting function. By activating this, big arrows will be presented above the sites, and the area of the archaeological locations are highlighted by projecting a signature colour directly on the terrain (see Figure 6).

Graphical solutions

Real-time rendering presents major limitations, because all elements that are visible on the screen have to be processed and rendered extremely fast (dozens of times per second). This means that visual elements directly impact performance and feasibility of the simulation, and need to be optimised and prepared for this specific usage. It is also important to note that modern mobile devices are able to handle rather large amounts of geometry and other visual information, but it is still quite easy to exceed the supported limits if one is not careful.

The main characteristic of the 3D terrain model that can be adapted and optimised is the level of detail: in particular polygon and vertex count. Since the terrain model is a continuous, triangulated, smooth mesh, the vertex count and polygon (triangle) count are directly related. For this reason, we will only talk about the polygon count and refer to the number of triangles.

The Krøgenes terrain was created in two stages. During the first stage, less detailed information of the terrain was obtained in a DEM (Digital Elevation Model) file format, which is the usual format to store elevation data of the Earth's surface and all objects on top of it. This file format contains height information and therefore it can be exported as a black and white image (a height map), where black represents the lowest point of the terrain and white represents the highest one. This black and white image can then be used to create a 3D mesh. Now, to convert the image to a 3D mesh, a flat and very detailed uniformly distributed mesh is created first. The height map is then used to displace the mesh according to the brightness of each area in the image, creating the 3D shape of the terrain. Figure 7 shows the height map and Figure 8 the resulting 3D mesh. The mesh was then optimised (discussed in detail below). For the creation of the 3D mesh we could use almost any 3D program that is used for 3D polygonal modelling, since the necessary steps can be reproduced

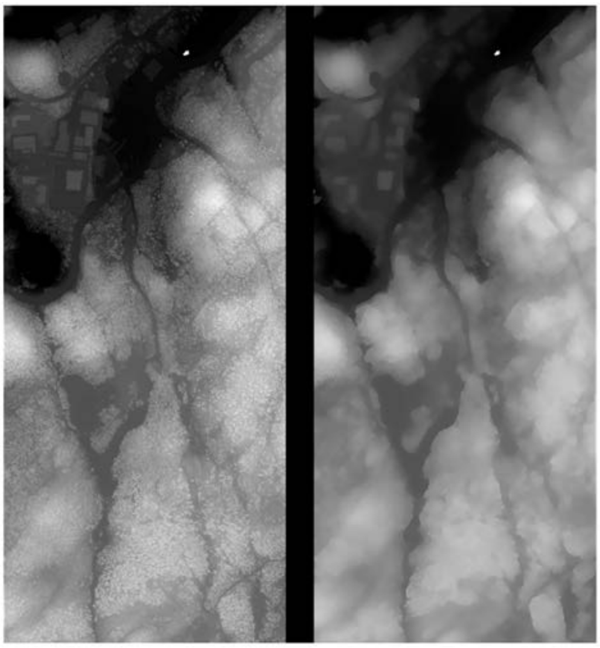

Figure 9. Removing noise caused by vegetation.

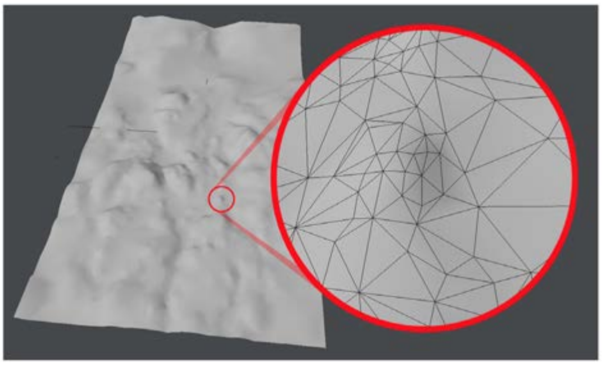

Figure 10. Optimized initial mesh.

in most of those programs. However, Lightwave3D was chosen, because it was familiar and we were well aware of its capabilities.

The second stage was entered when a much more detailed height map was obtained for the main area of the terrain. A very similar process was followed, but there was one additional step: the new height map was so detailed that it included vegetation height, which looked like noise for the most part. Because of this, the height map had to be smoothed out to remove the minor details, but keep the essential shapes of the terrain. A Photoshop filter called 'Surface Blur' was used for smoothing by applying it multiple times with different sets of parameters. What this filter does is blur areas where the local contrast is low, which means that small unnecessary details are removed, whereas greater differences in height are not affected. The initial and the resulting images can be seen in Figure 9.

After transforming the new height map to a 3D mesh, it had to be integrated into the initial mesh. Since it only covered a part of the necessary area, that area had to be cut out from the initial mesh and the new mesh had to be manually inserted and connected into the newly created opening. The resulting mesh was also optimised to reduce the polygon count.

The terrain is a natural object and therefore has an irregular shape. This means that some parts are more detailed than the others, which allows us to optimise some parts more by keeping more polygons on the detailed areas. In addition, the important areas of the simulation are predefined, and the user will not be able to see other areas close up, so we can use more polygons on the important areas at the expense of

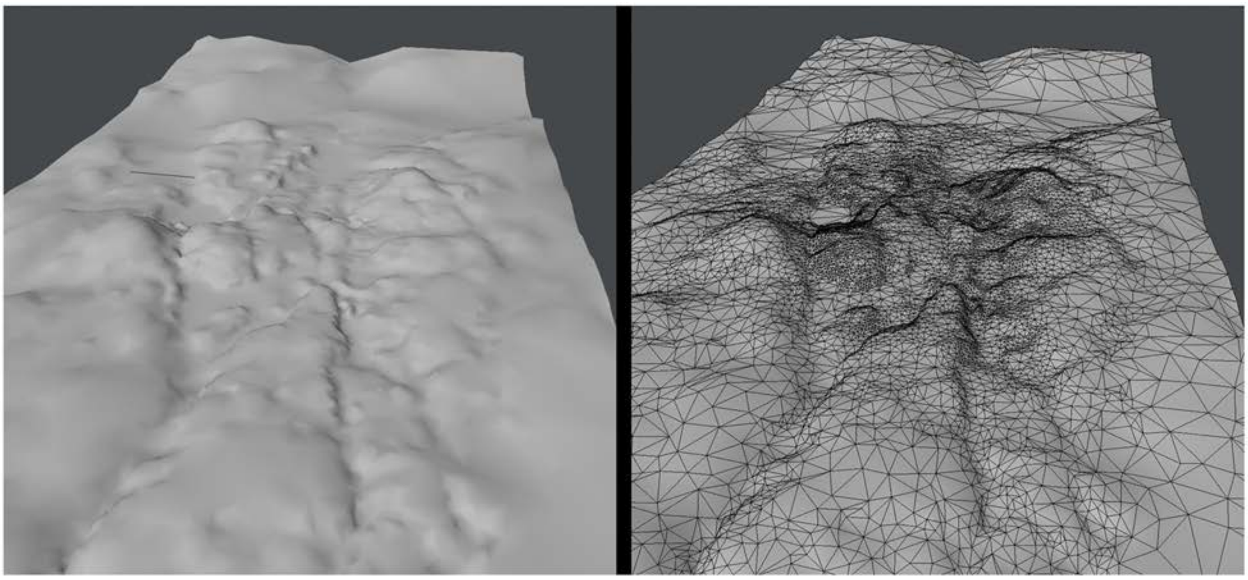

Figure 11. Resulting terrain model, wireframe mode to the right.

Figure 12. Users with iPad and the Krøgenes sitsim activated on location. Experience has shown that it is advantageous to tilt the artificial camera about 15% (photo on the right). This is done to avoid the screen from blocking the real view of the surroundings. In actual use there is no problem combining the two perspectives. On photo and video, however, the vertical displacement looks rather confusing.

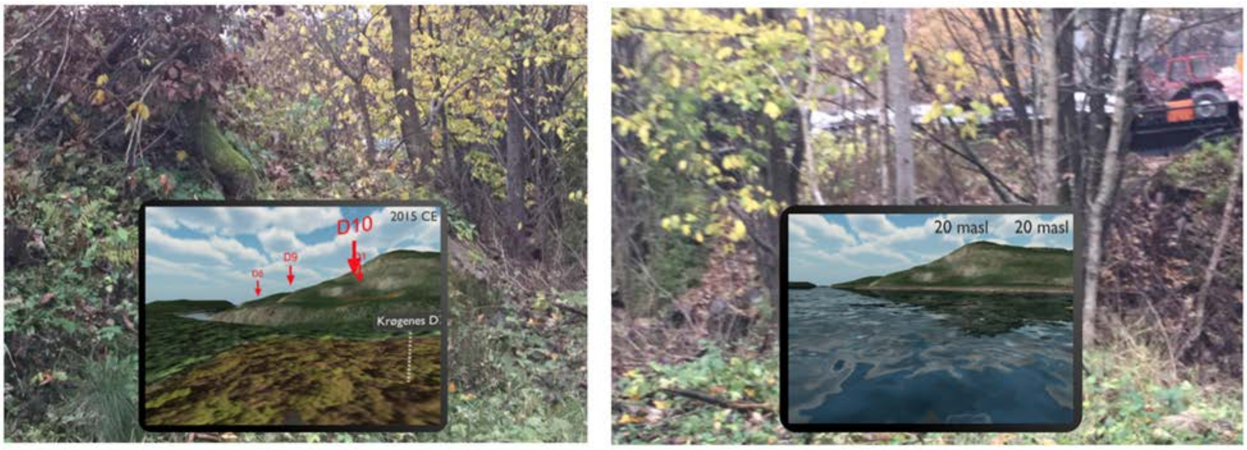

Figure 13. Two illustrations using the now/then photo montage feature in the app. A picture is taken with the real and the artificial camera at the same time. In this case the 15% tilting of the artificial camera is not operational (as in Figure 12). Both images are produced on location D2 looking south west. In the illustration to the left the sea level is set to present time and the feature to show the position of other stone age sites nearby is active (red arrows). Visible in the virtual perspective (frame) is also the hypertext link to the online database. In the illustration to the right, produced from almost the same position, but oriented more to the right (west), the sea level is set to 20 meters above current level and thus flooding the lower parts of the site.

the ones further away. Having these factors in mind, we can use a semi-automatic mesh optimisation tool that takes into account a predefined importance map (to specify the important areas) and the shape of the mesh in specific areas. In this particular case a third-party Lightwave3D plug-in called 'PLG Simplify Mesh' was used, outlining automatic mesh simplification techniques (Hoppe, 1999; Zelinka and Garland, 2002).

The overall optimisation is performed in three major steps:

1. Optimise the polygon count by reducing it on the areas with simpler shapes (other areas are usually also reduced, but less).
2. Assign the importance map to the terrain and optimise the further areas even more.

3. Manually fix the issues that are presented by the automatic calculations on the mesh (skewed polygons, random sharp edges, etc.).

The optimised initial mesh can be seen in Figure 10. The shape of the terrain is still similar to the one in Figure 8, but the mesh itself is more irregular and has far fewer polygons. The same optimisation process was applied to the mesh that was created from the more detailed height map, and the resulting terrain model is shown in Figure 11. The wire-frame (black lines) on the right side indicates the edges of the polygons, so the differences between the levels of details can be clearly recognised from the illustration: the main area of the terrain is much more detailed than the outer areas, and the flatter areas are sparse in comparison to the ones with more complex shapes.

Testing and evaluation on location

The trail involved a small group of adults (2 women and 4 men, age 39–74); all of whom to some extent were involved in work related to archaeology, cultural heritage museums and/or public administration. Most of the participants had smartphones and were familiar with or owned an iPad. None of them were regular players of video games. When arriving close to the sites, a short introduction to the technology and the application was given to the participants. Then each of the users was given an iPad, the sitsim-application was activated and they started approaching the designated sites D2 and D7, thus using the app to actually locate and move to the sites. At the two sites they accessed the database information and tested other features in the app, such as 'Bird's view' to better observe the other sites in the area and how they were positioned in the landscape relative to the one they were actually visiting. The ruler for changing the sea level was constantly used to see how it related to the present site and others in the surrounding environment. The invited testers also accessed the archaeological databases online for the various sites exploring photos of artefacts, maps and written documentation. After the testing the participants answered a written questionnaire consisting of 16 questions.

In general, the feedback from the participants was very good and confirmed our previous experience with similar tests (Liestøl *et al*., 2011). They quickly mastered the basic skills of operating the sitsim and found it easy to use. Some complained about a problem with the electronic compass, which in some cases caused the digital environment to drift sideways (a problem which now has been corrected). When asked about the added value of using the application on location they stressed the visualization of the sea level and how the various Stone Age sites were located in the landscape. This was considered a new and exciting experience, which they suggested could be deployed in a variety of contexts: excursions with school children, general mediation to the public at large (including senior citizens), as a valuable supplement to lectures etc. The possibility of accessing the online databases was also positively received, but it was noted that the layout needed adjustments to better accommodate the touch interface and the tablet screen. Asked how the simulation could be improved, several features were suggested: more detailed information about the findings, other types of relevant information, for example: vegetation, biology, fauna, natural resources, geology, narratives etc. It was also mentioned that the textures for vegetation could have more detail.

Conclusion and further research

Given the limited time and funding for developing the Krøgenes prototype the test showed that this is a promising deployment of Mobile Augmented Reality and the sitsim platform, and that it can enhance archaeological field work and mediation in various ways. In future versions we will focus on improving the detail of the terrain and the vegetation types, preferably by including 3D-models for trees, brush etc. It is also important to increase the number and positions of hypertext links to represent different kinds of information, not just one link for each excavated site, but related to location of individual artefacts, reconstructions of the excavation etc. We will also start work on how open data sets for terrain and vegetation can be accessed and exploited directly online, reducing the amount of manual adaptation required and thus extending the area which could be covered infinitely, in principle.

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A Virtual Reconstruction of the Sun Temple of Niuserra: from Scans to ABIM

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Abstract

In 2010 an Italian team started new investigations in the Sun Temple of Niuserra (Cairo). The archaeological survey of the site was planned in order to re-examine the monument after its discovery in 1898. The work is mainly aimed at a general re-evaluation of the archaeological data still available on the site, in order to establish a new plan of the temple. More than 100 scans and several 3D models by digital photogrammetry have been acquired. In order to make all 3D data sets for different targets available, a Building Information Modelling (BIM) project has been developed. Thanks to this new approach, currently underdeveloped in archaeology, it is possible to produce categories of environmental and technological objects which represent the 3D semantic of the model. The paper deals with all the recent achievements, especially regarding the conceptualisation of the architectural model.

Keywords: BIM, 3D, virtual reconstruction, sun temple, Egypt

Introduction

In January 2010, an Italian archaeological mission started new investigations in the Sun Temple of Niuserra at Abu Ghurab, about 15km south of Cairo, Egypt (Figure 1). This monument, built by the sixth ruler of the fifth dynasty (about 2400 BC) in the royal necropolis of the time, is the first temple completely dedicated to the cult of the sun in ancient Egypt. Moreover, out of the six sun temples known from the historical sources, the temple of Niuserra is the only one which is still largely preserved and visible nowadays.

The importance of analysing this temple is thus clear, particularly when considering that the temple was first discovered by Ludwig Borchardt in 1898 (Borchardt, 1905) and, since then, it hasn't been investigated (Nuzzolo and Pirelli, 2010, 2011).

The state of preservation of the temple has also been dramatically deteriorating in recent years. This state of disrepair is astonishing when comparing the current ruins of the temple with the pictures from Borchardt's time. In most cases, in the latter pictures it is possible to see clearly some architectural elements of the temple which are no longer visible. For this reason, the archaeological investigation of the temple was aimed, first and foremost, at re-evaluating the archaeological data still available on the site in order to create a new plan and an architectural reconstruction of the temple.

The Sun Temple of Niuserra is a quite monumental complex, surrounded by an enclosure wall of about 110 m × 80 m and composed of the following parts (Figure 2):

- a central courtyard aligned with the main entrance;
- an alabaster altar for cult offerings and rituals in the centre of the courtyard;
- a corridor — originally roofed — which runs along three sides of the courtyard itself (northern, eastern and southern);
- a large area, in the northern side, occupied by warehouses and purification basins;
- a 'cult complex', in the southern side, composed of two contiguous rooms which are usually named 'Chapel' and 'Room of the Seasons';
- a truncated pyramid-like basement with a superimposed structure, usually called 'the obelisk', in the centre of the temple enclosure. The basement and the obelisk occupy an area of 1600 sq. m and are currently preserved up to a height of about 13 m.

Besides traditional archaeological methods and goals, however, the mission was also aimed at creating a 3D digital model of the temple, by means of laser scanning and digital photogrammetry (D'Andrea *et al.,* 2014). The construction of a 3D model and the acquisition of relevant data presents not only important technological aspects, but also gives us the possibility to compare the new survey with Borchardt's reconstruction provided in 1905. His reconstruction, however, presents many

Figure 1. The location of the Sun Temple of Niuserra on Google Earth.

inaccuracies, especially in concern with the shape of the central obelisk.

According to the German scholar, this part of the temple was shaped as a huge, wide obelisk (20 m wide and 36 m high) on top of a pedestal (called from now on the 'basement') in the form of a large, truncated pyramid (40 m wide and 20 m high). An ascending corridor probably went up twice all around the basement, finally reaching the base of the obelisk on the eastern side. Because of the severe state of disrepair of the whole building already in Borchardt's time, his reconstruction was mainly based on the shape of the hieroglyphic in the contemporary tomb of the fifth dynasty priest Ty at Saqqara, where the name of the temple is determined by a two-stepped building in the form of a squat obelisk on a large basement. Borchardt compared the ratio between the two parts of the hieroglyphic sign with the archaeological evidence still available on the site, including the dimensions of the core masonry of the basement, the sloping of both the granite casing at the bottom of the basement (about 76°) and a limestone block probably from the obelisk (about 81°), the surface of the pedestal at the height of 20 m, and the surface of the base of the obelisk, which was believed to stand in the centre of the pedestal. Taking into account all these elements, Borchardt estimated the total height of the complex at 56 m (Borchardt, 1905, pp. 33–40). However, although we can accept the idea that the outline of the hieroglyphic sign used to determine the name of the temple in the inscriptions approximates the actual shape of the obelisk, it is not realistic to expect an exact correspondence between the proportions of the real building and those of its representation in the hieroglyphic text. Furthermore, a number of other considerations concerning the architecture of the temple (weight, height, type of material used, nature and composition of the soil where it was built, etc. ...) lead us to conclude that Borchardt's reconstruction is not entirely sound (Nuzzolo and Pirelli, 2012, pp. 666–669).

This paper, however, will not deal specifically with all the above problems, which mainly concerns the Egyptological milieu. Rather it is an attempt to show a new methodological approach for the management and sharing of archaeological and 3D data, applied in a specific study context. This new methodological approach is the Archaeological Building Information Modelling (ABIM), by which means it is possible to produce categories of environmental and technological objects and sub-systems, which represent the 3D semantic of the acquired model.

After a short introduction on the implementation of the digital survey of the temple, the paper will focus on the strategy of analysing the core structure of the architecture and its main components. Attention will also be paid to some recent achievements and technological issues, regarding especially the conceptualisation of the architectural model. Contrary to the traditional CAD or 3D graphics approach, a BIM project represents a digital environment which enables the integration of different elements of the 3D, from the basic x, y, z properties of the geometry to the physical and functional features of the 3D object. BIM

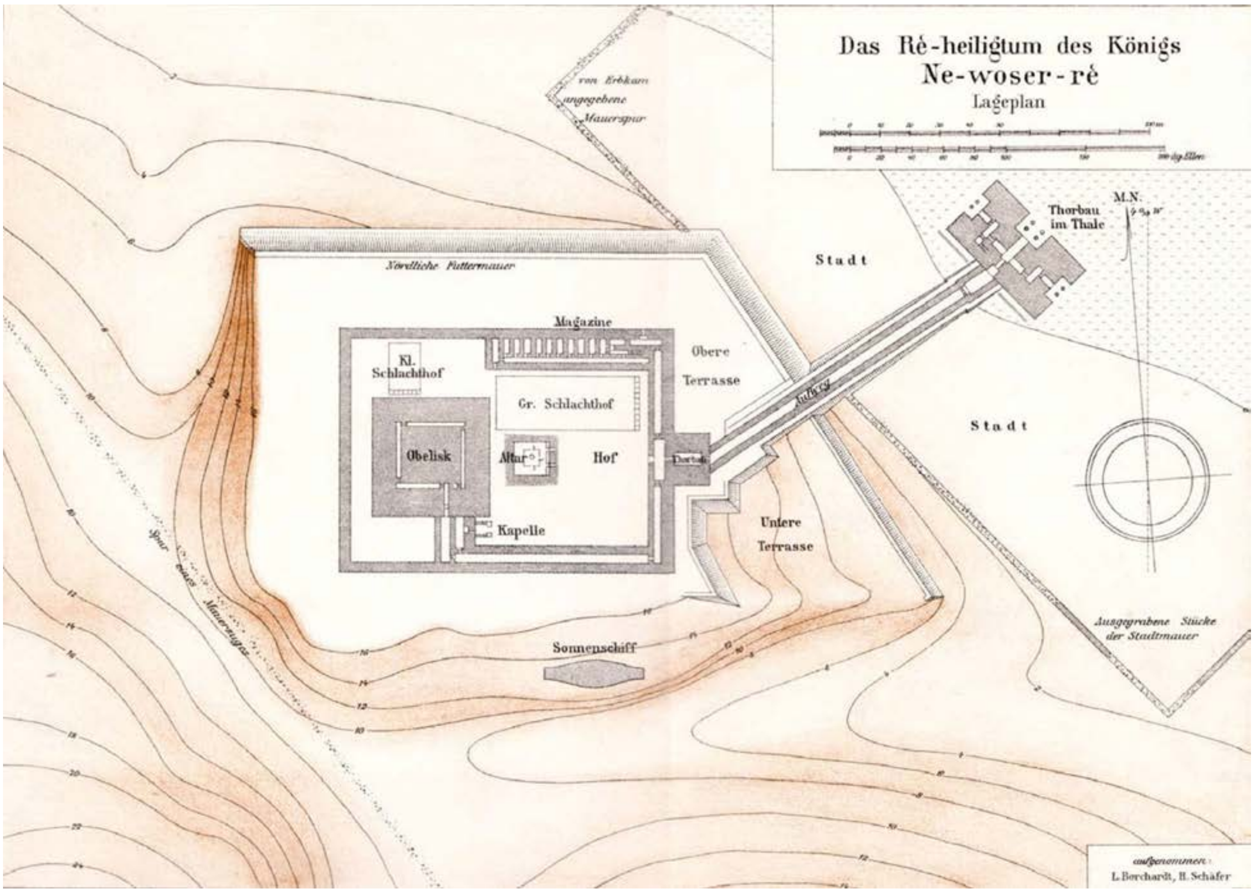


Figure 2. The Sun Temple of Niuserra. General map (Borchardt, 1905).

is a new technology (or methodology) which allows the association of different data and information useful in all phases of analysis, from the reconstruction to the conservation planning.

The digital survey

According to a well-established workflow, the work on the site has been divided in three different phases:

- Acquisition and revision of the graphical documentation of the solar complex of Niuserra and vectorisation of the most relevant archaeological features unearthed in the previous explorations;
- On-ground analysis of the state of conservation of the area and of the archaeological evidences; verification of the data acquired during the first phase;
- Design and implementation of the digital survey of the solar temple by means of 3D laser scanner and digital photogrammetry; post-processing (clearing, filtering, alignment and registration) of the shots, 3D reconstruction of the solar temple and extraction of the main graphical features (sections, elevations, plans) of the monument.

During three campaigns (carried out in 2010 and 2014) different surveys have been carried out with the aim of reconstructing the overall archaeological area of temple of Niuserra. As already mentioned, the complex presented many gaps and missing parts due to ancient and modern robbery activities, as well as to the collapse of some structures. This complicates any interpretations of the architectural remains. For this reason, the design of the data-acquisition was particularly accurate in order to avoid errors in the reconstruction; in particular, many scans from different point of views were carried out to completely acquire each single object.

To guarantee the correct roto-translation and alignment of the scans, a local grid was implemented by positioning four pegs around the temple, following the shape of a rhombus, and one peg at the top of the terrace structure. The positioning of the pegs was carried out with a total station. The topographical network was closed by linking the first and the last point, in order to reduce possible errors in measurement.

In 2010 (January and December), two different data-acquisition campaigns were carried out with the aim of surveying the Chapel and the Room of Seasons on the southern side of the temple, as well as the storehouse on the north–eastern side, and the area of the obelisk and the altar in the central part of the temple.

All scans were processed, registered and aligned on the base of the targets measured by total station. As the laser scanner cannot acquire colour data, some photos were taken by a digital camera and then superimposed, using software JRC 3D Reconstructor®, on the final 3D model in order to have a much more realistic rendering.

Finally, different maps and sections documenting the state of conservation were extracted from the model; in particular, a top view map, showing the perimeter of the obelisk, the internal corridor and the collapse of the core masonry walls on the south-western corner, was generated. Finally, some plans were built thematically on the basis of the materials of the blocks used for the outer and inner core of the obelisk. These maps were then superimposed on the original plan, drawn by Borchardt, in order to compare the reconstruction obtained from the model with the survey carried out in the last century.

In 2011, during the Egyptian revolution, the temple was partially damaged, including some parts of the floor of the court and the obelisk masonry. The main damage was concentrated in two areas:

- the room of the seasons, whose pavement was consistently broken in the centre and later on repaired, perhaps by the local guards;
- the big stairway of the so-called storerooms, in the north-eastern corner. This ramp was completely destroyed, thus losing important data for this kind of structure (in the Egyptian architecture in the same period only few remains of stairways leading to the roof top of the temple are known).

Furthermore, the topographic grid created in December 2010 was completely removed.

In 2014 a new 3D survey was undertaken using a Faro Focus 3DX130. This device mounts a high resolution digital camera, particularly useful for acquiring not only the geometric features of the temple, but also to provide a completely realistic 3D model of the sanctuary. Furthermore, the new type of laser scanner acquires geo-referenced data allowing a simpler and easier way to merge the different scans.

In 3D data–capture, special attention was dedicated to some specific areas of the temple which proved to be very problematic for both the final reconstruction of the monument and the presence of important and numerous artefacts which could be useful for the archaeological analysis of the temple and the drawing of its revised plan.

The 2014 laser scanning campaign was conducted on the whole of the temple with three main focus areas:

- the obelisk (especially its basement which is still quite well preserved);
- the area around the altar, where several inscribed blocks of granite are still visible on the ground;
- the entire enclosure wall of the monument and the main doorway of the temple (attention was here particularly paid to the analysis and scanning of blocks of the structure laying outside the wall).

In six days, 56 scans were acquired. Fourteen high resolution scans were processed and aligned and used as reference for the other ones from the previous campaigns. Then all scans were merged into one point cloud. Finally, the duplicated points were removed and the model simplified in order to have a lighter 3D reconstruction without losing any information useful for the interpretation (Figure 3).

To reach a more realistic rendering of the archaeological area, the laser scanner campaign was integrated with several acquisitions by image-based modelling. The integration of the geometric precision of measurements by laser scanner with the high resolution texturized surfaces by image-based modelling approach, allows us to analyse in detail the remains and to provide information about the materials and architectural elements of the sanctuary.

Some critical areas, fundamental for the reconstruction of the obelisk and the entire monument, were in particular acquired by the image-based modelling method:

- the main Gate of the temple;
- the area of the so called 'Slaughterhouse, especially the area of alabaster basins (Figure 4);

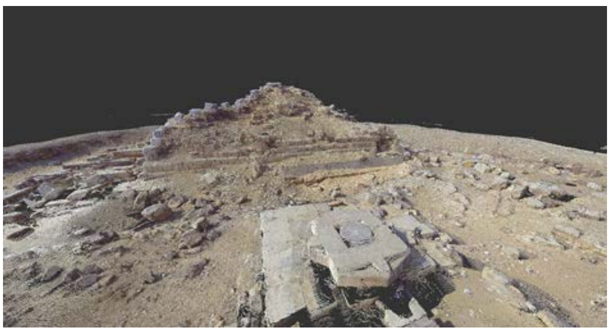


Figure 3. The 3D model of the Sun Temple of Niuserra after alignment of all scans.

Figure 4. The 3D model, by image-based modelling, of the area with alabaster basins.

- the collapsed blocks laying at the bottom of the obelisk at its south–western corner.

Data acquisition has been carried out by a reflex Canon 450d with 18 mm lens. For each area, an entire working day was spent. The photos were processed by Agisoft® Photoscan®. Some targets were positioned close to the areas to be investigated in order to scale the model according to its real dimensions. To check the precision and accuracy of the model, some points were also extracted from the scans in order to geo-reference the model to the grid taken by the laser scanner. At the end of the processing different models (point clouds and mesh) were rendered.

All the 3D data were, finally, merged and analysed to highlight the damages caused to the archaeological structures after the 2011 revolution. Moreover, many annotations, associated with short descriptions, were taken for those blocks and architectural elements which were collapsed and had not been placed by Borchardt when the temple was discovered.

The digital archive so far produced contains some Tb of data, which are not easy to manage with traditional methods. On account of the increasing volume of acquired data, in 2014 a new approach started to not only facilitate a typical scientific workflow (formulation of alternative hypothesis about the reconstruction of the obelisk, analysis of the structural architectural elements still *in situ*, creation of plans, sections and drawings), but also to create a more advanced model for data-sharing which may eventually facilitate the study of the relationship of the temple with the surroundings monuments and the local environment. The next paragraph examines in detail this new approach, in particular the design of the architectural project, the preliminary results so far achieved, and future perspectives.

The BIM approach

The acronym BIM defines a new methodological process of modelling architectural data and not simply a graphical software for 3D modelling. To be precise over the correct interpretation of BIM, it is necessary to recall, among many others, the following two definitions:

1. BIM involves representing a design as objects — vague and undefined, generic or product-specific, solid shapes or void-space oriented (like the shape of a room), that carry their geometry, relations and attributes. The geometry may be 2D or 3D. The objects may be abstract and conceptual or construction detailed. Composed together these objects define a building model (not a BIM, in my view) (Eastman *et al.*, 2008).
2. Building Information Modelling (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition (National Institute of Building Sciences, 2016).

According to these definitions, BIM is a philosophy or a process to design, collect, share and manage different data sets. BIM has been formerly employed for modern civil engineering to integrate the needs of the designers with the world of the building companies and industries. From this point of view, BIM has been implemented to facilitate the design and management of new buildings by creating a digital environment accessible by different stakeholders. Notwithstanding these native features, BIM has also been applied to manage existing and historical buildings. In 2009, some scholars (Murphy *et al.,* 2009) introduced the definition of H (Historical) BIM to describe an approach focused on the conservation and virtual reconstruction of ancient buildings. Later Murphy (2012) highlighted that HBIM is '*a novel prototype library of parametric objects, based on historic architectural data, in addition to a mapping system for plotting the library objects onto laser scan survey data*'.

Even if BIM had not previously been implemented for built heritage, the need to share and combine several categories of data into a unique system, such as the state of conservation, the description of single architectural elements, information about spatial organisation of the buildings, the use or the reuse of spaces and objects, the classification of objects, encouraged different scholars to apply this new approach to cultural heritage. The main challenge of BIM is therefore to manage different data sets relating to a building during its complete life-cycle by including spatial and alphanumerical data. In wider terms, BIM can be considered as an evolution of GIS in a 3D environment, as it associates geometric and spatial element to attributes and relationships among objects (Tobiáš, 2016); 3D alphanumerical and spatial data about the architecture of a building can be integrated in BIM as 2D objects are integrated into a GIS.

A strong advantage of BIM is the possibility to freely share 3D data from various sources, providing to various experts the access to the same model. Thanks to BIM, each user can access, analyse and modify whatever part of the model by participating, actively, in the same project. BIM encourages the various actors to collaborate, without obliging them to acquire a new language. In the end, BIM is the result of different and interconnected models which exchange and share data coming from topographical investigations, laser scanning or digital photogrammetric surveys, or traditional modelling techniques.

Contrary to the CAD approach, the 3D modelling BIM is based on parametric elements representing all physical and functional properties of whatever architectural object with its spatial relationships. The model is therefore described through a formal representation highlighting concepts and categories (Murphy *et al.,* 2011).

To reach this target software companies are developing a common format to facilitate data exchange. Industry Foundation Classes (IFC) is becoming the standard as it can guarantee a reduced loss of information in the exchange among the different applications and actors. This format allows the creation of a virtual and common repository where anyone can store and share information concerning the geometry of a building or its material or historical information.

Whilst in modern civil engineering the libraries of parametric elements can be easily implemented and shared, in the field of HBIM there are not libraries suitable for the 3D reconstruction. If, in built heritage, the architectural elements are frequently well preserved (Quattrini *et al.,* 2015) and therefore the creation of categories of objects is a quite simple task, whereas in the archaeological context the structures are very often badly preserved and only partially visible or strongly restored or modified compared to their original shape. The absence of shared libraries has probably made the application of BIM more difficult for archaeological monuments and sites (Scianna *et al.,* 2015; Garagnani, 2012).

Currently in HBIM field, researchers are facing two main challenges:

1. the creation of standard libraries of architectural elements sourced from data acquired by digital surveys (laser scanner and/or digital photogrammetry) (Brumana *et al.,* 2013; Oreni *et al.,* 2014);
2. implementation of tools to facilitate the re-modeler of the 3D data point clouds according to parametric libraries (Chiabrando *et al.,* 2016).

Our project deals with the design of a specific library for the technological system adopted in the building of the monument. The next paragraph focuses on the workflow developed for the implementation of BIM; in particular, we face the formalisation of data based on an innovative composition and decomposition of all the architectural elements.

A BIM model for the Sun Temple of Niuserra

Thanks to the campaigns carried out up to and including 2014, the temple of Niuserra was completely surveyed. As BIM deals with the environment and technological systems, the first step was the analysis of the architectural model in order to facilitate the composition and decomposition of all elements according to different levels of detail. From the 3D model architectural information was extracted about the building and the masonry. All the blocks and slabs were singularly analysed in order to highlight elements showing the design and the building of the different structures. This preliminary work allowed us to correctly formalise the whole complex according to UNI 8290–1981 classification set-up for building systems. It consists of:

> PART ∩ COMPONENT ∩ SUB-SYSTEM ∩ ELEMENTARY SYSTEM ∩SYSTEM
> (∩ = it belongs to)
> SYSTEM — It corresponds to the whole Solar Temple;
> ELEMENTARY SYSTEM — It consists of classes of technological units and the main systems for the working of the temple: structure system, closing, internal and external partitioning, etc.;
> SUB-SYSTEM — They are the technological units of each elementary system, as the foundation and horizontal and vertical partitioning, etc.;
> COMPONENT — They are the classes of the basic technical elements as architrave, jambs, internal and external walls, etc.;
> PART — It includes each element identifiable as a component like blocs, slabs, etc.

Even though this classification has been developed for modern civil buildings, it fits well with the features of Egyptian architecture, which shows the following main elements: Simplicity; Modularity and Standardisation; and Portability.

While in the previous approach, the 3D survey was mainly used to extract 2D sections and maps useful to document the shape of the monument and its state of conservation, thanks to BIM it has been possible to setup a wider workflow allowing the creation of spatial and geometrical 3D objects enriched by a formalised description. The first step of this new project was the import of the scans into a BIM. To clean and merge all scans in only one point cloud, which is more easily managed by BIM, all 3D data were imported into Autodesk® Recap®. The processed point cloud was then imported into the software BIM Revit® by Autodesk®.

As Revit uses a different language to describe the technological system, one of the main tasks was to map the categories of schema based on the UNI standard onto conceptual groups of Revit. This is the final mapping:

UNI	**Revit**
System	Family
Sub-System	Type
Component	Instance

Even though BIM has been developed to design new buildings, in the case of Niuserra, and usually for HBIM, this approach was upturned; HBIM has to start from the visible evidences on the ground to achieve the reconstruction of the prototype of the monument.

Thanks to BIM, the concept of drawing or modelling of whatever building can be easily completed and enriched by creating a new and more complex workspace. The new model is a simulation and shared laboratory in which we can rebuild the different phases of the construction process ranging from single blocks to the entire building.

As different parts of the temple had been partially damaged, because of the continuous reuse of stone in antiquity, it was fundamental to localise the exact positioning of the no longer *in-situ* architectural elements. The technological system was probably also used in the contemporary and nearby pyramids, and therefore some missing architectural elements were based on the analogue remains in Abusir.

From the analysis of the conceptual model, some categories of architectural elements, corresponding to different components of the technological and constructive system, have been extracted (Figure 5).

These semantic parts contribute to the formal and physical representation of the 3D reconstruction of the monument: on the basis of the 3D survey, different 3D geometrical objects have been created and associated to a description including code, material, dimension, and provenance (Figure 6).

Each element of the sub-system has then been analysed and correctly assigned to a specific category. Revit allows the creation, in the architectural model, of a taxonomy including families, types and single instances. As Revit has been designed for industry, a fundamental step of the project implementation was the creation of a new parametric library which included a detailed description of all archaeological artefacts. Thanks to this formalised data-organisation, called ABACI in Revit, BIM allows us to associate physical instances to graphical, photographical and archival information (Figure 7). The database can be easily queried and the geometrical objects visualised. In this way, BIM works as 3D GIS.

The conceptual design of Revit, particularly flexible in the starting phases, allows to analyse all components and to create classes or entities of standard volumes which can be integrated in the model. These entities can be progressively converted into virtual building materials; detailed architectural elements can be created (walls, roofs, pavements, etc.) on the basis of their volumetric families. In this way, one can also easily calculate the amount of building materials necessary for the construction of each part or sub-system of the

TECHNOLOGICAL SYSTEM

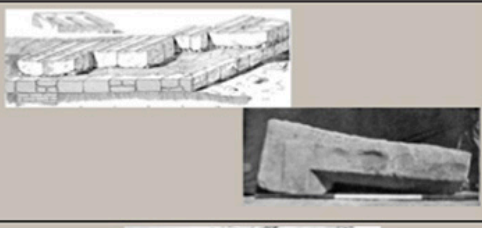
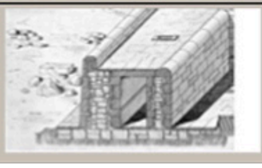
classes of technological unit	technological units	classes of technical elements
Closing. Set of technological and technical elements of the building system with a function to separate and to conform the interior spaces of the building system itself than outside.		
	**vertical closure** set of vertical elements of the technical building system with a function to separate interior spaces of the building system itself than outside.	- perimeter walls - vertical external fixtures
	**lower horizontal closure** Set of horizontal technical elements of building system having function of separating the interior of the building system itself from the underlying soil or the foundation structures.	- Slab on the ground - horizontal fixtures
	**Horizontal closure of outdoor spaces** Set of horizontal technical elements of building system having function of separating the interior of the building system itself by underlying external spaces.	slabs of open spaces
	**top closure** Set of horizontal technical elements of building system having function of separating the interior of the building system itself from outer space above	- covers - horizontal external fixtures

Figure 5. The Technological System schema for the closings of the temple.

temple and evaluate what it misses or what has been destroyed (Figure 8).

In order to better analyse the final reconstruction, the model was contextualised into surrounding territory. By assigning correct geographical coordinates it was possible to visualize the monument in its landscape and to improve the rendering of the building material according to the positioning of the temple. This approach is particularly useful to not only generate correct shadows in the animation, but also to deepen the spatial location of the monument, as it was probably used as astronomic point of observation. Furthermore, Revit allows the visualization of the reconstruction in Google Earth®. This overlapping was particularly useful to better understand the artificial terrace system used for the foundation of the temple.

Different historical maps were used to analyse the creation of the complex. As hypothesised by Borchardt, Niuserra's temple was installed on a previous building whose traces are still partially visible on the ground. To attempt to identify the two monuments (or layers of a single monument) the reconstruction was superimposed onto the old map provided by Borchardt (Figure 9).

The reconstruction allows us to hypothesise some alternative proposals. In particular, the simulation of horizontal planes and rebuilt structures can also help us in the understanding of the original architectural structure of some of the temple components. This is extremely important for the obelisk, whose shape has not yet been clarified and represents one of the main targets of new investigations. The superimposition of the point cloud onto the conceptual mass of the obelisk highlights the co-planarity of the planes and volumes of the building. In some areas, phenomena and dynamics of collapse or movement of the blocks can be better identified, and therefore useful for the final reconstruction of the monument (Figure 10).

Another example is provided by the south–eastern area. Here it has been possible to understand the outflow system of the liquid by creating a virtual plane among the few visible remains of the pavement with the alabaster basins positioned along the South walls.

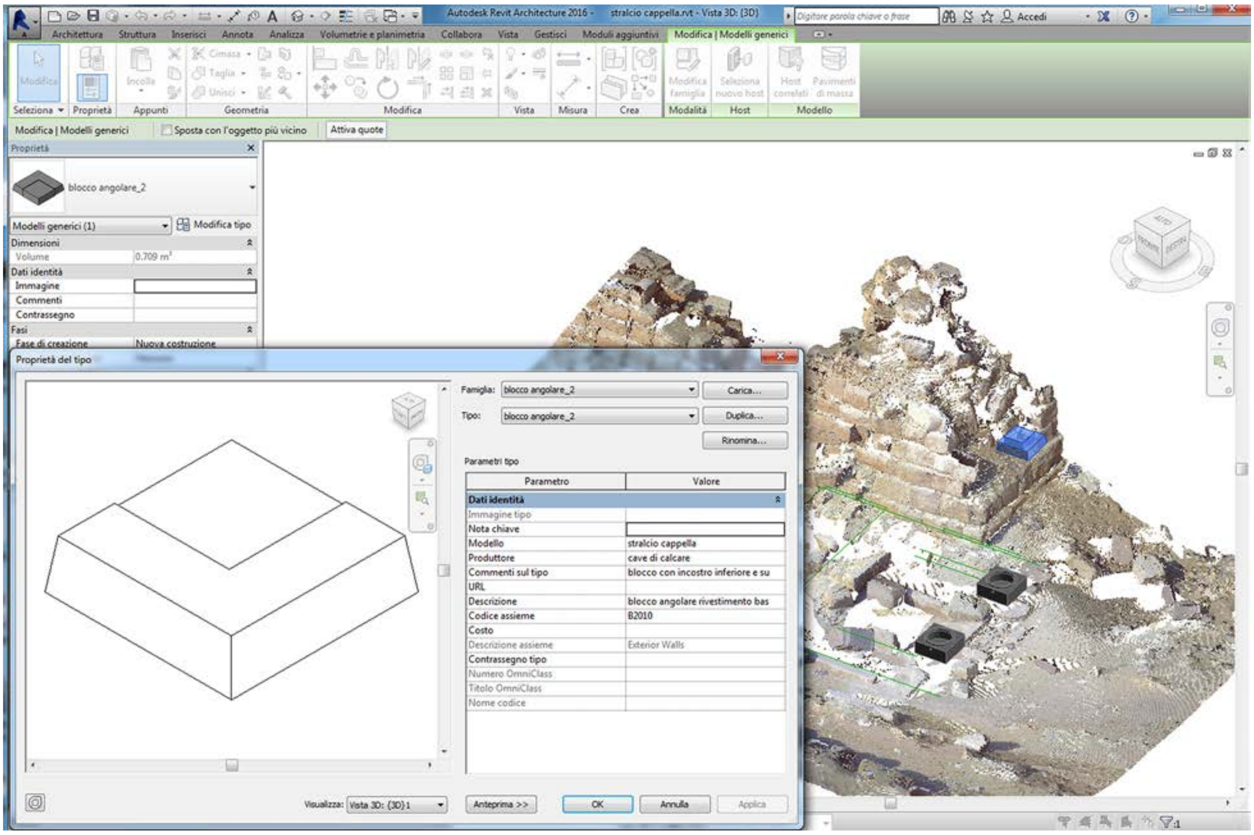


Figure 6. An example of types: an angular block (highlighted in blue) and its description.

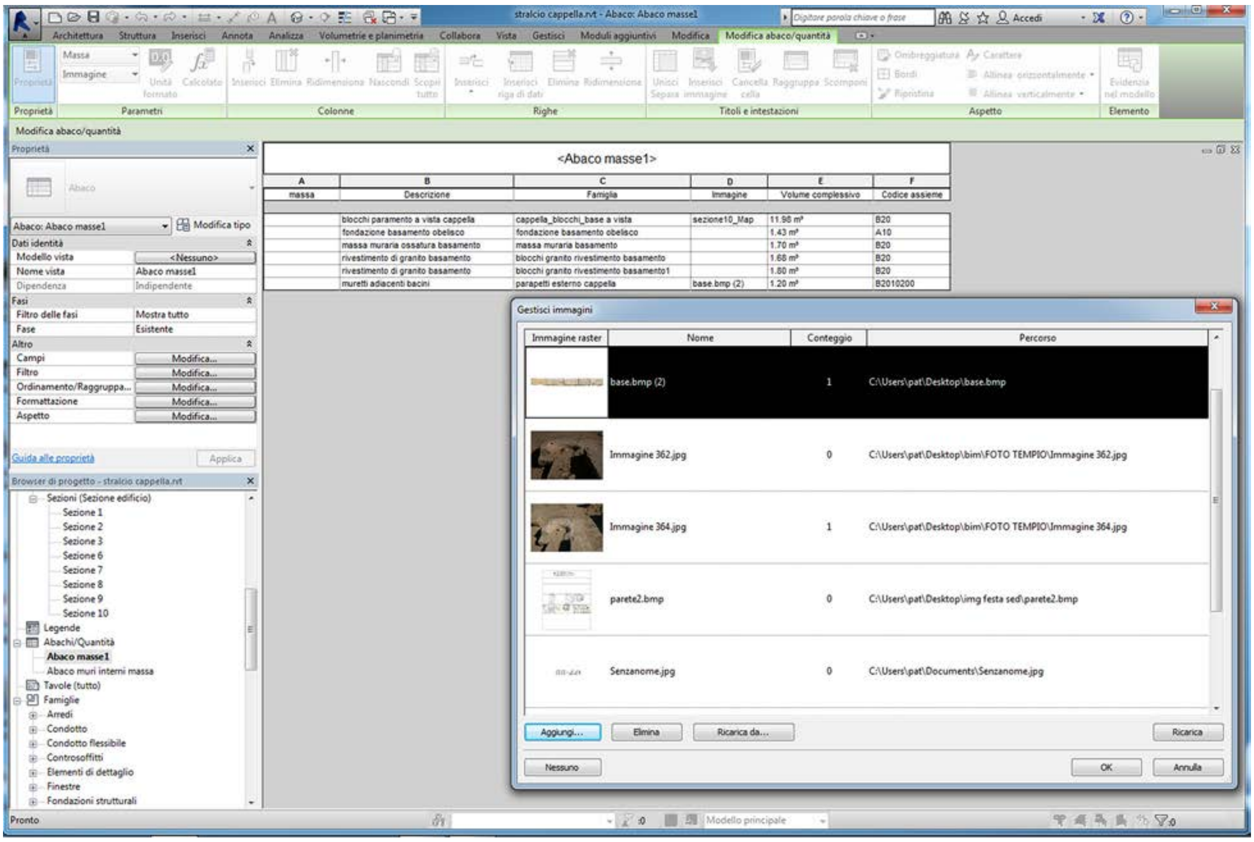


Figure 7. A list of some components of the Sun Temple of Niuserra associated to the images.

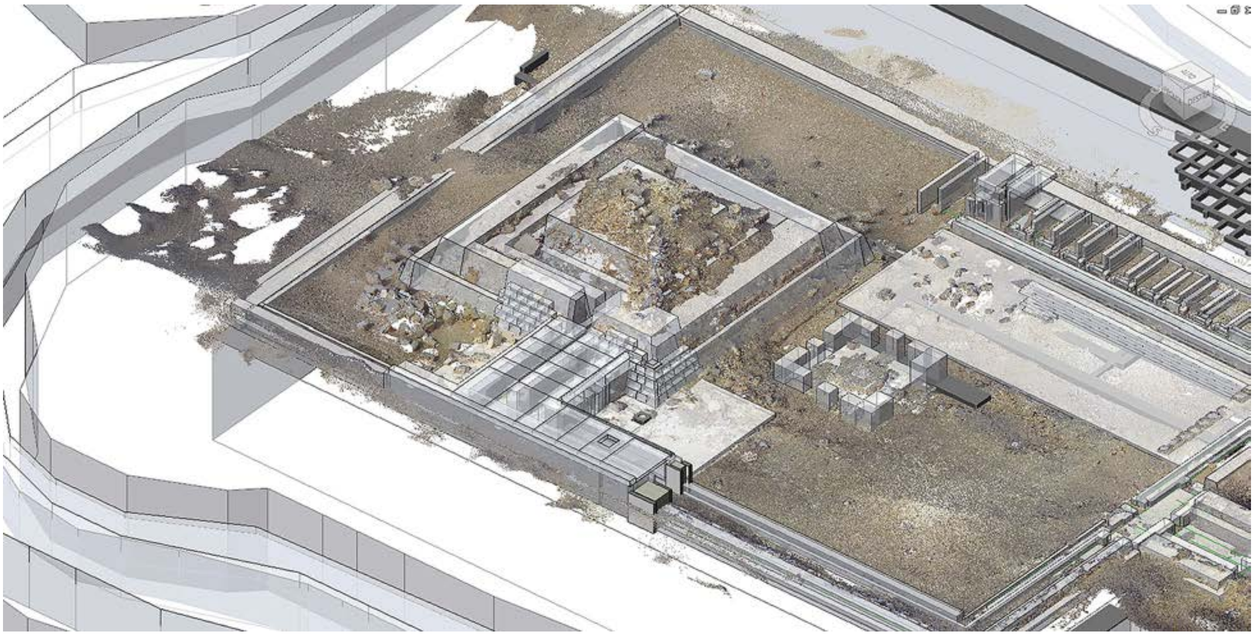


Figure 8. The visualization of the 3D model of Niuserra; in particular, different rebuilt blocks superimposed on the digital acquisition

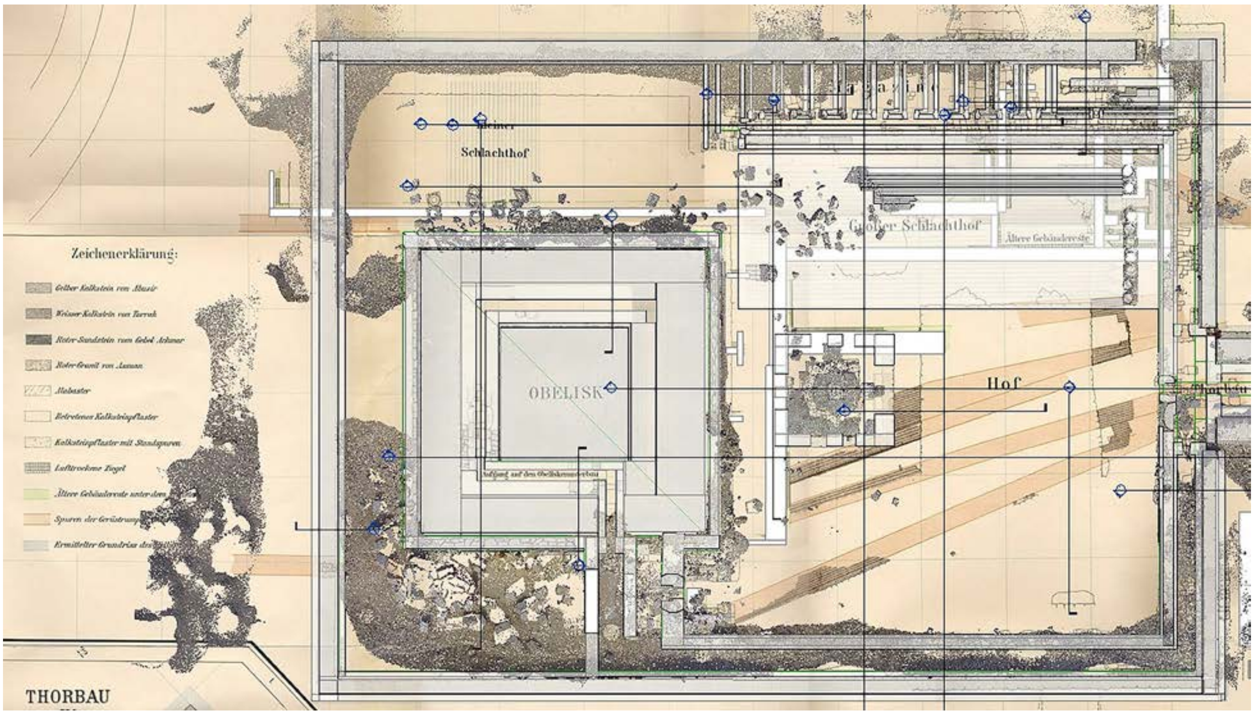


Figure 9. The superimposition of the reconstruction onto the Borchardt's map.

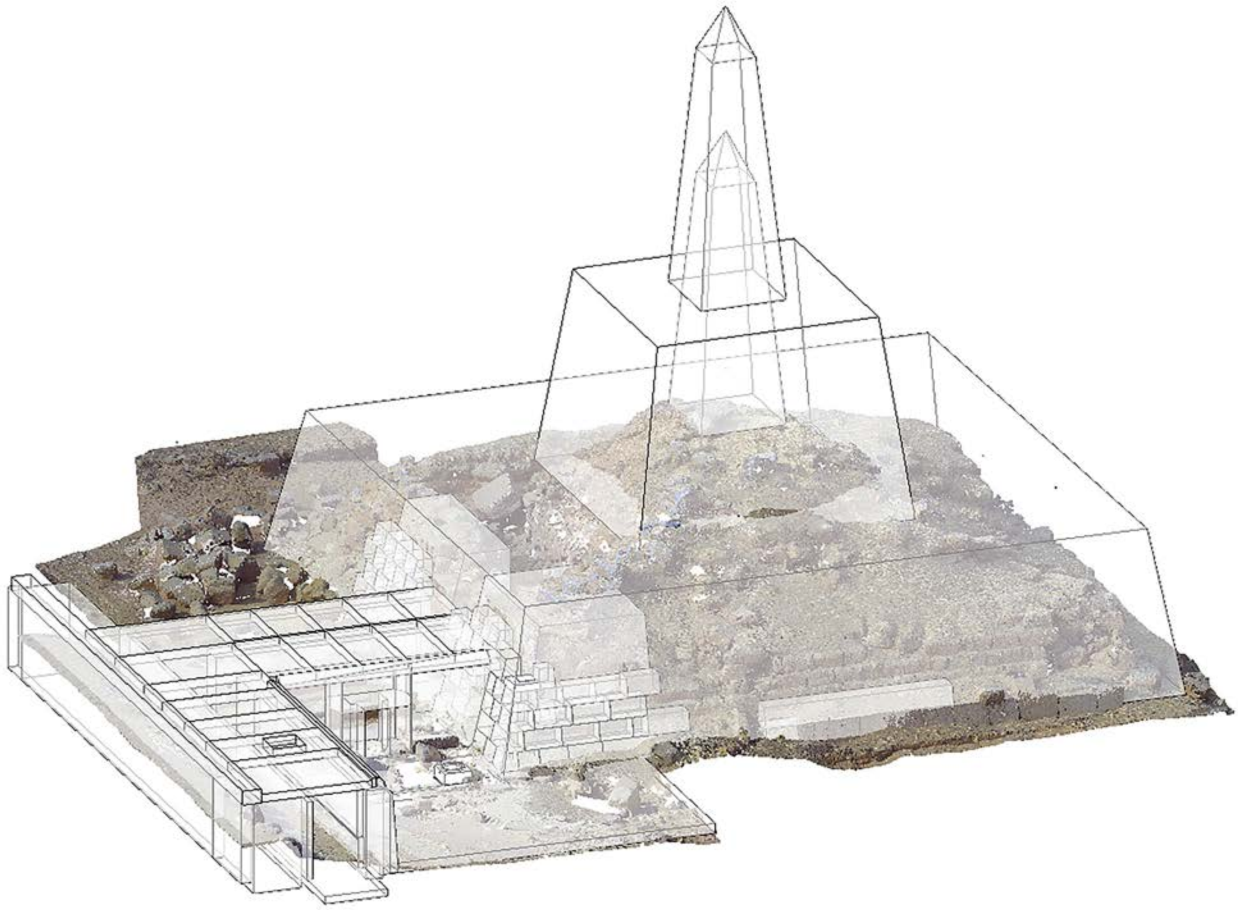


Figure 10. The comparison of two alternative hypotheses about the height of the Obelisk.

Conclusions

The paper dealt with the preliminary results of a BIM implementation for an Egyptian monument characterised by many missing parts which do not allow a precise reconstruction by means of traditional methodologies. The model is based on a number of highly accurate scans and 3D models by photogrammetry, and it is finally enriched by a detailed description of all the available architectural elements (either masonry blocks or decorative slabs and other decorative elements).

The BIM approach, which is currently underdeveloped in archaeology, was started in 2015, replacing the previous approach based on a traditional 2D Geographical Information System (GIS). The architectural model includes environmental and technological categories which allowed for a preliminary analysis of the static position and orientation of the building, as well as of the sun positioning. To enrich the graphical model of the temple, an objects library has been implemented in order to describe the structural elements formalised as categories and families according to Revit. All data are fundamental to investigate the use of the monument in antiquity and the following destruction, which probably started already during the pharaonic period.

The BIM gives us the possibility to create a semantic structure including different levels of parametric objects and types. This library can be reused to describe contemporary monuments which are dated to the same period and have similar functions. The standard format (IFC), which collects all information, ensures the exchange of data among different scientists and experts with no lack or loss of information.

In this way, the final model can be easily exploited by various experts to start a new analysis regarding the static, the seismic and the possible causes of the collapses. All this information is also necessary to plan eventual restoration projects or valorisation initiatives.

The BIM, in the specialised applications as HBIM and A (Archaeological) BIM, is a new and reliable approach for the representation of built heritage. It associates the high quality of the model with an accurate geometry and a detailed description of each component of the architectural system. For these features BIM will play a fundamental role in forthcoming years in the management and sharing of 3D content. Thanks to the possibility to encapsulate the semantic in the model, BIM will soon become a virtual laboratory for cognitive systems in archaeology.

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A 3D Digital Approach for the Study and Presentation of the Bisarcio Site

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Abstract
Recently, 3D-from-photos and close-range photogrammetry have established themselves as important modern technologies in archaeology. Nevertheless, three-dimensional survey has not reached its full potential in the daily work of excavation, as it has been generally restricted to exceptional and monumental cases.
The digging of the late- and post-medieval cemetery of Bisarcio, Sardinia, was an opportunity to experiment with 3D survey. After an extensive 3D survey, covering the entire excavation area and duration, 3D models have been used for the documentation and interpretation of the stratigraphy, and, to create a web-based visualization and dissemination tool.
The three interconnected steps, of documentation, interpretation, and visualization and dissemination, were used to evaluate the effectiveness of the 3D data in each step, and also to build a complete 3D workflow.
The results are promising: with the correct protocol, these procedures may be soon part of the archaeologist's daily routines.

Keywords: photogrammetry, 3D survey, digital workflow, interactive visualization, dissemination tool

Introduction

The use of 3D survey in archaeological excavation started some years ago, employing terrestrial laser scanners. However, its practical use was extremely limited, due to the cost of scanning devices, the long processing time, and the scarcity of software tools usable by the archaeological community to exploit the generated data effectively.

The game-changers for this field have been the 3D-from-photos and close-range photogrammetry technologies, that have now reached a good level of maturity and ease of use, coupled with the availability of software tools (directly usable by the archaeologists), capable of manipulating and presenting high-resolution 3D data.

Our idea is that 3D surveying will reach its full potential when it is deployed as a daily instrument:

- integrated with the standard excavation procedures, and with specific protocols,
- carried out extensively in both time and space, recording the whole work area for the entire duration of the excavation,
- providing a fully-digital documentation-study-presentation workflow.

The experimental case we are undertaking aims to present an integrated workflow, where a three-dimensional survey was carried out as a daily tool to record an excavated stratigraphic sequence in its entirety. The 3D models generated were then used to document the process and to interpret the stratigraphy. The interpreted data was finally published on the web through an interactive 3D viewer.

This test case will show how it was possible, even working in a didactical student excavation, to define procedures and protocols able to effectively use the 3D technologies to build an integrated documentation-study-presentation workflow.

The case study has covered the use of 3D surveyed data in the different phases of work:

1. the extensive day-by-day 3D survey during excavation,
2. the use of the 3D surveys for the study and interpretation of the stratigraphy,
3. the use of the 3D surveys, plus the results of the interpretation, for dissemination purposes.

It is not uncommon to find 3D-from-photos used as a surveying tools during an excavation, or to use 3D models to produce the technical documentation of a site, or to use the digital 3D representation of an excavation for dissemination and presentation purposes. Individually, these three stages and their relationship with 3D data have already been investigated in various publications (Berggren *et al.*, 2015; Olson *et al.*, 2013; Dellepiane *et al*., 2013). The idea of this experiment, however, is to build up a fully integrated workflow, able to make comprehensive use of the data coming from the 3D survey.

In each of the steps, beside trying to optimise the procedures and protocols characteristics of that specific step, care has been taken in making sure the results of the stage were ready-to-use for the next one, trying to build-up a cost-effective workflow.

The 3D survey relied on 3D-from-photos techniques (also called Structure from Motion, or Close Range Photogrammetry (Barnes, 2011). These techniques are known for being low-cost, but they are also time-effective and versatile. It has already been demonstrated that, if applied correctly, the 3D data produced is perfectly appropriate for the use in archaeological surveying (Green *et al*., 2014; De Reu *et al*., 2014; Fiorini *et al*., 2011). In most cases, the 3D surveys have been focused on specific findings or areas, or a specific time frame of the excavation. In this case study, the photogrammetric survey has been carried out extensively with respect to both space (covering the entire excavation area) and time (daily, throughout the whole excavation period).

The 3D models generated constitute a very accurate and complete recording of the archaeological context, which have then been used both in the documentation and analysis stage, and in the interpretation stage. In this way, all the contexts that has been excavated and removed during the digging operations have found a new virtual life (according to the stratigraphic method). The 3D models have been very useful for analysing the relationship between the contexts, and also between the contexts and the dating materials uncovered.

Finally, the 3D models and the results of the interpretation step have been used to set up an online visualization tool, targeted at experts, able to convey visually (and interactively) the different phases of the excavated site. With the use of the 3DHOP tool, it was possible to design and setup an interactive web-based visualization, using the high resolution 3D models generated in the survey, and connecting them to the data collected and interpreted during and after the excavation process.

Our experimentation could be considered a good opportunity to define effective protocols to use in the different steps of the excavation: the day-by-day surveying and documentation of the site, the study and interpretation phase, and in the subsequent communication and disclosure stages, especially when addressed to specialists.

Figure 1. The archaeological site of Bisarcio is located in central North Sardinia: a strategic place for Sardinian Middle Age starting from the end of the 11th century.

As the case study was a university excavation, this project was also a precious educational opportunity in which university students could understand and learn the basic principles of a new way (for our community) of surveying, archiving and managing excavation data during the excavation campaign.

The case study

The test case chosen is Bisarcio, a medieval and post-medieval site in north central Sardinia. It was a prominent place with high strategic importance for the history of the island, as it was the diocesan seat from the late eleventh century, and the village was inhabited until the first half of eighteenth century. The Sant'Antioco cathedral and the bishop-citadel ruins are, nowadays, part of a local cultural tourist route.

The archaeological excavation was carried out by the Medieval Archaeology chair of the University of Sassari, History Department, Human and Education Science. Digging operations took place in different trenches all over the site: the village, the bishop-citadel and the village cemetery. As the excavation is still an ongoing project, the results of the campaigns so far are still unpublished.

The three-dimensional survey here described was applied to the cemetery context. In this kind of environment, the archaeological process implies, after an accurate investigation, the context's removal and demolition. Generally, these contexts are rarely reconstructed for museum purposes, and it is difficult to exploit and valorise them.

Figure 2. The archaeological site of Bisarcio in an aerial image. Bottom: the Basilica and the bishop citadel. Top: beyond the street the area of the abandoned village, that covers a 4 hectare area.

Figure 3. The Sant'Antioco di Bisarcio Cathedral; a west–east oriented cathedral, and the bishop citadel area. Left: beyond the perimeter wall you can see Area 5100, at the beginning of digging operations.

Figure 4. Area 5100: in the background, southwards, the west wall of the cathedral. Right: the perimeter wall of the bishop citadel.

The cemetery (area 5100) was chosen then as the ideal case study. Area 5100 is located near the north wall of the Sant'Antioco cathedral, and the east wall surrounding the bishop's citadel. The excavation area is 10 meters square.

The tombs in the Bisarcio cemetery are characterised by simple ground trenches, without any brick structures or headstones to mark their presence. A detailed survey was necessary to produce useful documentation. Furthermore, the cemetery area was used before the medieval period, therefore, accurately recording the tombs before removing them was mandatory to understand and analyse earlier contexts.

Excavation was aimed to verify the presence of the cemetery area of the abandoned village of Bisarcio, close to the ecclesiastical building. Geomagnetic analysis

Figure 5. The excavation area seen from the south to the north, with the 10 meters square during digging operation close to the uncovered tombs.

in 2012 documented the existence of underground quadrangular structures (walls) surrounding area 5100. After a three year dig, the excavation data highlighted the highly informative potential of the stratigraphic sequence: in this part of the Bisarcio site, it was possible to record human activities over seven centuries.

The data presented in this work belongs to the excavation campaign carried out in 2014, in the trenches 1 and 2, located in the southwest part of the area 5100. So far, excavation campaigns have demonstrated the existence of four different inhabiting phases from Late/ Middle Ages to the present day. Among these various stages, two different burial phases are the most relevant for this experimentation.

The experimentation stages

Our objective has been to set up an interconnected working pipeline, in order to test not only the effectiveness of the use of 3D survey in each step of the work, but also the possible benefits of having the entire workflow based on 3D data.

We consider 3D data to be less refined than traditional documentation, but the data is highly accurate and easily adaptable. The data from 3D models is a more neutral and 'raw' representation of the state of an excavation than the classical documentation, which is more informative on its own by virtue of interpretation, but less adaptable. The adaptability of the 3D generated data facilitates the transition from one phase to another.

The day-by-day survey

The 3D survey was carried out side by side with the traditional topographical survey (Bianchini, 2008; Kavanagh *et al.*, 1996), in order to obtain a richer documentation. The main goal, in this stage, was the definition of an operating protocol (set of rules/ pipeline), able to cover the entire site but still time-effective, and usable by the students. By applying a precise working protocol, we also hoped to obtain ready-to-disseminate results.

Survey activities followed a precise strategy, designed before starting the dig. All of the contexts dug were documented in the same way, without any selection of a subset of the stratigraphic sequence.

The survey pipeline followed the same steps for each context, but each step was customised to the specific characteristics of the archaeological context to be documented:

1. automatic coded markers were positioned on the contexts surface (at least four for every layer acquired),
2. sketches and technical drawings were made in order to graphically represent context

boundaries and extension and also marker location,

3. the photographic acquisition of each layer, in terms of number of photos and area to be covered) was tailored to the specific features and characteristics of the layer to be recorded, but followed the common guidelines established at the beginning: constant lighting conditions, sharp focusing on the photos, regular coverage of the layers, no use of flash,
4. a topographic survey of the photogrammetric targets through total stations (Leica TS02) was carried out, for scaling the models and for setting up the coordinate system (in the specific case, SRS Gauss Boaga Italy 40).

The survey of each context took around 20 minutes, and the time spent every day surveying the site was around one hour and a half. The survey required two people, positioning targets, surveying them topographically through the total station, and finally taking pictures, in each case following the same procedures.

Image acquisition is a fundamental stage in the acquisition process; the quality and scientific value of the photogrammetric survey depends on this step. Particular care was taken to ensure the images were of sufficient quality to obtain a good 3D reconstruction.

In total, 33 photographic sets were acquired during excavation to document 100 contexts. In total, 2,183 images were captured, with an average of 66 photos per set. All the images were taken using a Canon PowerShot SX50, with a 12 Megapixels resolution.

Using Agisoft Photoscan software, data processing was carried out following the standard procedures for the generation of 3D models from photos as follows:

- aligning photos / building sparse point cloud
- building dense point cloud
- building mesh (3D polygonal model)
- generating texture
- building orthomosaic
- exporting results

The 3D models were scaled to the correct size and geo-referenced using the markers, topographically surveyed, and visible in 228 of the input photos (The more photos are used to specify marker position, the higher is the accuracy of marker placement; every marker was visible in at least 2 photos). Markers were also useful to improve the photo alignment procedures.

While the photographic and topographic surveys took place during the excavation, in the standard daily time-frame normally allocated to documentation, the processing of the data set (3D model creation and geo-referencing) was done afterwards and lasted two weeks, mostly of pure computation time.

At the end of the processing, we had 33 textured and geo-referenced high resolution 3D models, ranging from 500,000 to 2 million triangles.

The 3D models for documentation and interpretation

The 3D models, correctly scaled and geo-referenced (thanks to the topographical survey) were the key in achieving a higher completeness and level of detail (and, often, also of accuracy) in recording the documentation. In addition to its metric qualities, the 3D models also acted as a visual, photorealistic representation of whatever the archaeologist had to destroy and remove to access underlying strata. This visual support, although only virtual, can be used to better understand, study, and interpret data, and it is more effective than a series of photos.

It is in this sense that the three-dimensional survey offers new opportunities with respect to the traditional on-the-field documentation process. Even if the documentation and interpretation method rely on a direct observation and on the physical presence, 3D models allow for a 'virtual return' to the excavation, also to the areas that no longer exist, making possible new measurements, new observations, and revising the physical relationships between the different contexts.

Through using 3D documentation, it is also possible to make an aggregation of the different documentation media on a common, georeferenced support. This allows the different members of the on-the-field team (archaeologists, anthropologists, survey specialists), to work on the documentation and access all the media produced, from within the same environment. This is also true for the post-excavation debriefing and study, and also when the data is accessed, later on, by another team working in the same area.

The documentation methods have not changed significantly in recent years. The on-the-field workflow of the archaeologist is quite similar to what it was years ago (D'Andrea, 2006, p. 79), and the only procedures that have been formalised at a national level are related to the filling of standard forms for each finding (De Felice, 2008).

Without any standardised procedure, it is difficult to establish nation-wide scientific protocols for the stratigraphic methods, to maintain the informative potential of the stratigraphy, and also to limit the loss of information when the produced documentation is subsequently re-used.

By exploiting the three-dimensional graphics, it is possible today to rethink the entire documentation workflow, exploiting the possibilities of the three-dimensional media in preserving a more complete and visually perceivable representation of the materials removed during the excavation process.

The potential of a 3D workflow are already evident in the survey and restitution phase, as the 3D models are more suited to help in representing a series of aspects which can be difficult to perceive from the classical documentation, such as the slope and depth of a trench, or the case of a wall with height irregularities or leaning: these features can be graphically drawn, often through hachures, but are more difficult to read (Medri, 2003; Puche, 2015). As these details are more apparent in a 3D model, it is easier to trace them when creating technical drawings, resulting in a more detailed documentation.

The outlines of the contexts and of the surfaces, which are amongst the most common technical drawings used as documentation, can be traced directly on top of the 3D models, creating vectorial profiles and contours without the need of a long drawing session over the excavation, and with a higher accuracy (Medri, 2003).

Also, the traditional transverse and longitudinal sections drawings can be directly extracted from the 3D models. Given the faster generation procedure (with respect to on-the-field direct measurement), it was possible to create a more complete and rich technical documentation. As all the 3D models are geo-referenced, the creation of cumulative drawings is also easier.

A side-product of a 3D photogrammetric survey are photographic orthomosaics; in this experimentation, the availability of this type of data made the generation of plans much easier, and prospects, increasing the speed of the production of the standard two-dimensional graphic documentation. As the orthomosaics are easier to generate using 3D-from-photos tools, with respect to classic image-compositing tools, especially in case of high detailed evidence, such as tombs and walls, the survey procedure is faster.

The online visualization tool

The third step of the experimentation was to create a web-based visualization tool, again based on the 3D models and the data generated in the interpretation phase.

When creating a visualization page, it is important to define clearly the communication aim (what is the message we want to deliver) and the target public (who will use the page). It is extremely complex, if not impossible, to design effective data visualization pages that can be useful to users of all levels, and cover all aspects of a complex technical project

In this case, what we wanted to achieve was a page showing to other archaeologists the main interpretations of the excavation data. With this idea in mind, the design of the visualization followed these guidelines:

- the aim is describe the **interpretation** of the site, the visualization will not give access to the entire excavation data set, but only to a selected subset. Moreover, the pages will be structured to highlight the relationship between the contexts as they have been interpreted by the archaeologists.
- people accessing the visualization will be **experts of the field**. So, it will be possible to use non-trivial navigation and rendering options, and advanced measurement and analysis tools will have to be included.

The visualization pages have thus been structured following the timeline and the logical elements of the site, in order to highlight: 1) the different phases of use of the Bisarcio cemetery, and 2) the various tombs in each specific phase.

The main page of the web visualization shows the excavation area as a whole, making it possible for the user to explore the site. A simple info panel contains the basic information about the excavation site.

On the bottom-right of the page, the timeline panel can be used to select one of the different phases of the cemetery; each phase has its own information panel, describing the specific period.

Each period shows a different 'global' 3D model, created from a set of coeval contexts, providing a view of the state of the excavation at that specific time frame. For those phases (already excavated) which correspond to a cemetery stage, the tombs are displayed in their respective position. Each tomb may then be selected, to access a detailed visualization page, presenting the contexts related to that specific tomb.

Each tomb has its own detailed visualization page, and all have the same structure. The page shows three contexts depicting different stages in the excavation of the tomb: unexcavated, excavated, and empty. It is possible to examine each stage individually, or turn on more than one stage at the same time (to compare them and use the sectioning tool).

It is also possible to turn visible or invisible a global model of the whole area, as a semi-transparent shape,

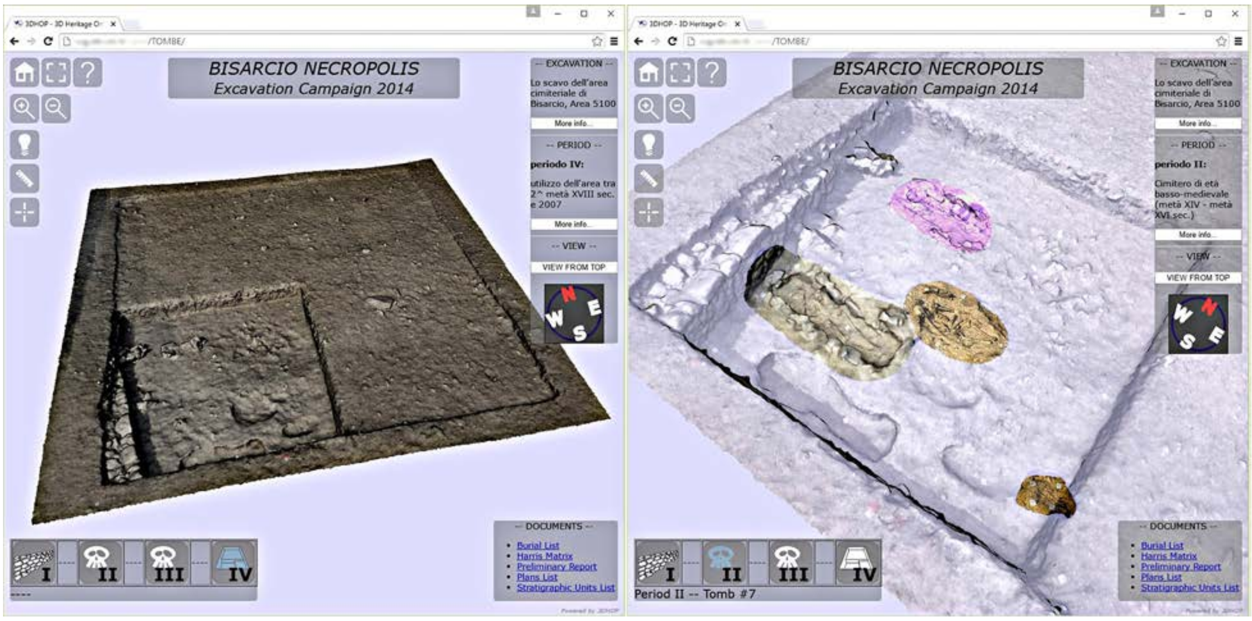

Figure 6. The 'global' visualization page of the excavation. Left: the starting view of the whole excavation area, with the timeline on the bottom-left corner. Right: once a cemetery period is selected, the tombs of that period are displayed and may be selected.

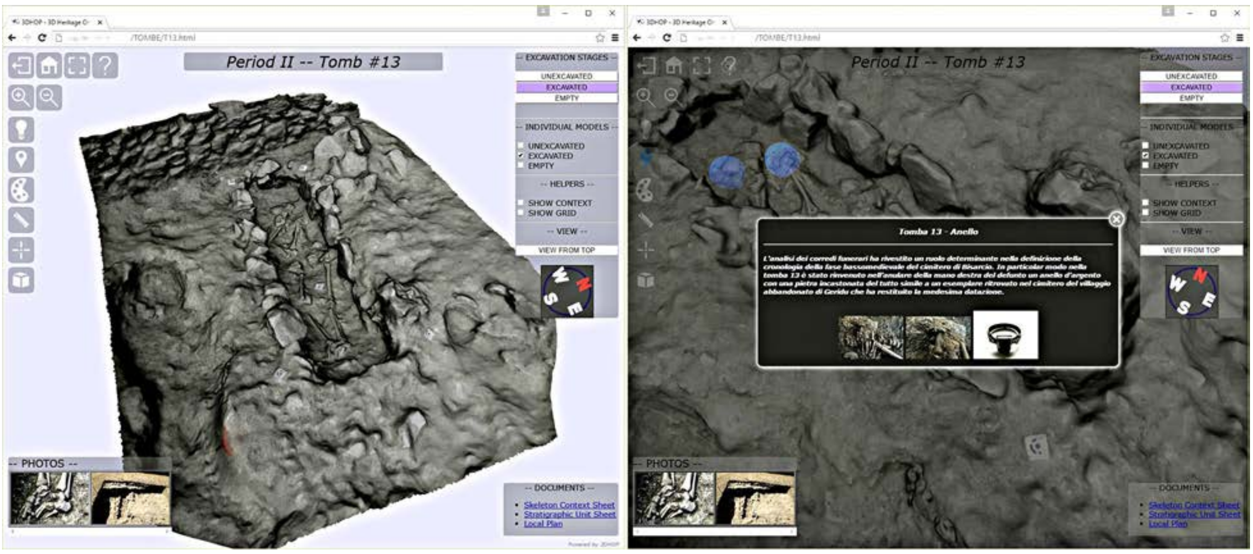

Figure 7. One of the detail pages for the tombs of phase II. Left: a view of the 'excavated' stage of the tomb. Right: the hot-spots and associated panels describing the small finds.

to better understand the spatial relationship of the tomb with the rest of the excavation. Tombs containing small finds also have hotspots. These are clickable areas on the geometry of the context, positioned according to the location of the find, which can be clicked to access a description panel detailing the find.

All the pages (the global timeline, and the single tombs) have direct links to pdf documents, images and other excavation documentation, thus providing a more structured access to the documentation corpus.

The navigation of the 3D terrain has been designed to be easy to use, but still able to reach any position on the 3D models; it is possible to zoom in/out, rotate around horizontally and move the point of view vertically, and to move around. Double-click can be used to move to a specific area, re-centring the model. The navigation of the general view and of the tombs has the same interface.

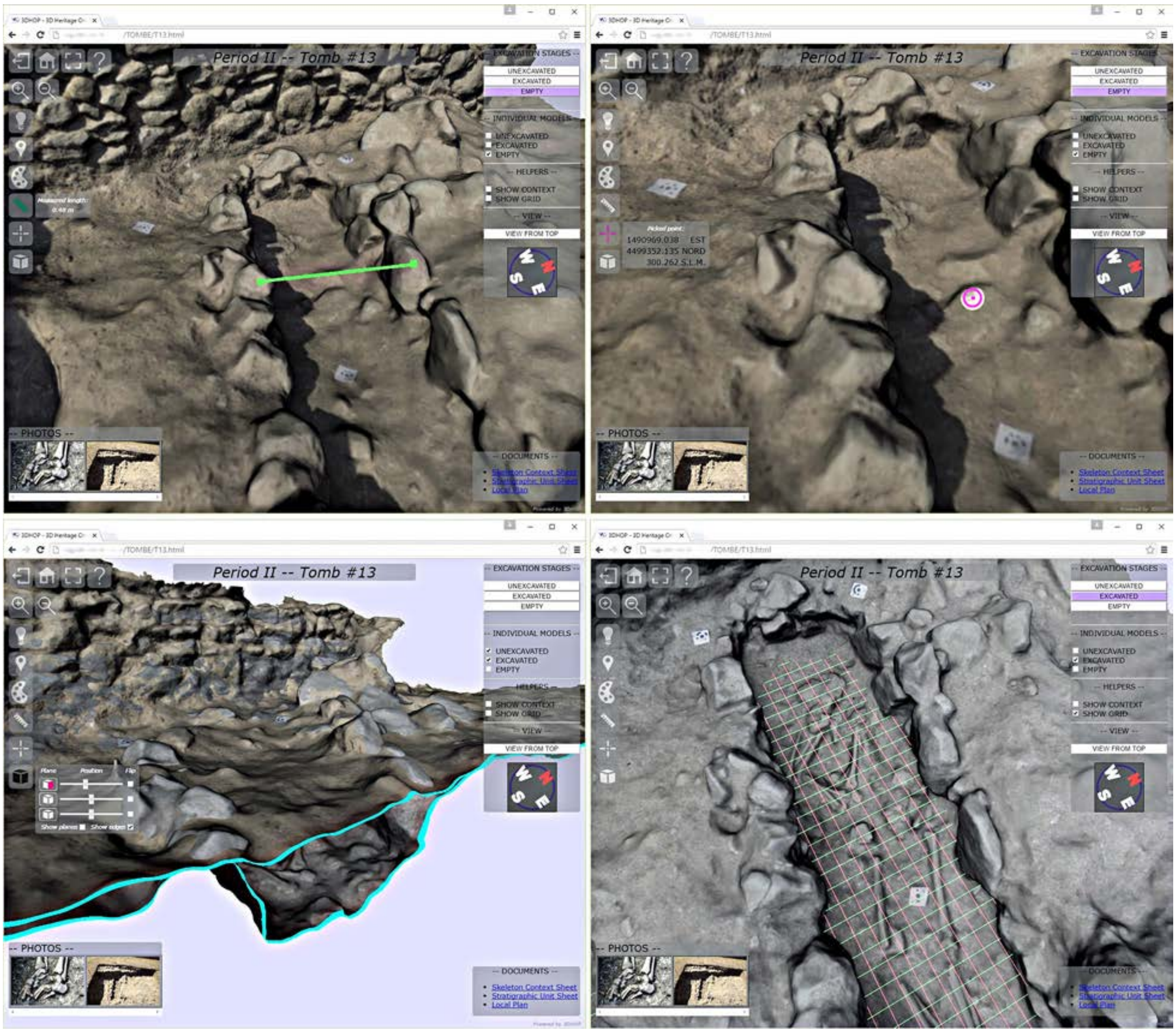

Figure 8. The various measurement and visualization tools available in the tomb detail page. Top-Left: point-to-point measurement. Top-Right: pick-point with georeferenced coordinates. Bottom-Left: interactive cut-through sectioning. Bottom-Right: reference graduated grid.

A compass helps to understand the orientation of the current view (and to reset the orientation to the north). A home button resets the view, and a 'from top' button brings the viewer orthogonal from above.

In order to better understand the shape of the ground, stones and objects, it is possible to change the lighting direction and remove the texture/colour information.

As all the 3D models are correctly scaled and geo-referenced, it is possible to use these visualization pages as a way of obtaining metric information. A point-to-point measurement tool is always available to take direct linear measurement over the shape of the excavation, and the pick-point tool returns the coordinates of any picked point (in the Gauss Boaga Italy 40 space).

In the tomb detail pages, it is also possible to use the real-time sectioning tool to 'slice' the ground along the main axis, to better understand the spatial relationship between the different surfaces composing the burial in its whole. A reference grid may also be superimposed to the 3D model, to better perceive proportions and dimensions.

The 3D web visualization uses 3DHOP, an open-source tool aimed at creating web-based interactive visualization of high-resolution 3D models (Potenziani *et al.*, 2015). The tool is based on HTML5, and runs natively inside the browsers, without the need of additional software or plug-ins.

By using a multi-resolution streaming, it was possible to put online the high-resolution 3D models of the different contexts. Data is also compressed, making the data streaming very efficient. The 3D models used ranged from 1 to 3 million triangles (considering also the models generated by merging different contexts), in most cases with a 4k texture.

This tool is designed to offer different interaction components and control functions. The idea is that these components may be configured according to the needs of a specific project, and connected to HTML components of the webpage, making possible to create complex visualization schemes.

The work on this project followed exactly this strategy: beside the design of the timeline-based exploration and of the 'global view' — 'tomb detail' page structure, most of the tools used (hotspots, measurement, sectioning) were already available in 3DHOP, and have just been configured to work according to our needs, while others (e.g. the compass and the reference grid), have been developed from scratch.

Conclusions and future work

We believe the experimentation was successful: by defining precise protocols, and with a minimal amount of resources, it was possible to obtain a complete 3D digital workflow, which allowed for an accurate and complete recording of the archaeological contexts, and has been useful both in the documentation and analysis stage, and also in the interpretation and dissemination stage.

In our opinion, three-dimensional photogrammetric survey is mature enough to integrate effectively and enrich the traditional on-field documentation, and, to some extent, overcome its limitations.

The main difference between the traditional on-field survey and the digital 3D survey resides in their respective nature. A traditional documentation survey relies on a selection of relevant features made in the field by the person in charge of the documentation. It is an *interpretation* of the data. It requires more time in the field, and produces more structured and informative results, but it is not an objective representation. On the other hand, a 3D survey provides a more objective and global recording of the state of the archaeological context: there is no selection, every detail of the context appears in the model (according to the resolution of the survey). Although 3D surveys can be quicker, in the field, and generate 3D models with a higher level of detail and realism, they will always need a step of refinement and interpretation to become a proper, usable technical documentation. By combining data coming from the two approaches, it was possible to obtain a richer and more precise documentation, and a more complete knowledge of the site.

In this case study, by using the 3D models as the base for the documentation process, it was possible to overcome some of the limitations of the traditional documentation process. The higher density of metric information had a positive impact on the accuracy and on the level of detail of the documentation. The possibility to visually revisit areas already removed from the excavation, helped in the documentation and interpretation process, as it allowed for a more thoughtful and careful study of the evidence.

Additionally, the results of a 3D survey are ready-to-use visual representations of the site, which can be easily used for dissemination to experts and non-experts alike.

A 3D photogrammetric survey also allows the capture of other kinds of usable data, like orthomosaic, which were used extensively in this experimentation to create technical documentation.

3DHOP can be considered a suitable tool to visualize on the web high resolution 3D models, and to connect them to the large amount of data collected and interpreted during and after the excavation process. It was possible to design and implement a visualization tool focused to a specific audience, still exploiting the same data produced in the previous phases of the workflow.

A possible further step in the experimentation would be to re-use the 3D models and data gathered during the excavation to build a different visualization tool, this time aimed at the general public. This would be possible, starting from the existing 3D models, and from the documentation and interpretation documents of the excavation, still using the 3DHOP tool. This would require a complete re-design of the visualization pages, to cope with the new communication aims and the different audience.

This tool would be an added value for this case study (a cemetery context), for which it is not possible to imagine or define a 'classic' museum function. This would represent another, almost direct 're-use' of the 3D survey data collected following the digital methodology, further lowering the cost/benefit ratio of this kind of survey strategy.

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Mieko Matsumoto and Espen Uleberg (eds) 2018. *CAA2016: Oceans of Data*
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
Oxford: Archaeopress

The Role of Representation in Archaeological Architecture

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Abstract
The representation, analysis and interpretation of elements of archaeological heritage is a painstaking activity. It also includes a wide range of interdisciplinary subjects and competencies. The interrelation between different disciplines opens up the possibility to achieve complete results as far as documentation, analysis and interpretation of the Archaeological Architecture (AA) are concerned. On one hand, the archaeologist can use explorable and measurable 2D and 3D high precision models, which realistically show surface qualities; on the other hand, architects can turn to their advantage archaeologists' extensive knowledge of correctly interpreting data in their historical and metric framework and to verify interpretative hypotheses.
The proposed paper, starting with the integrated survey of archaeological structures of high historical and artistic importance, like the Colosseum, Pantheon and Arch of Janus in Rome, analyses the possibilities offered by the survey and the representation of Archaeological Architecture at different scales.

Keywords: archaeological architecture, survey, representation, 3D/2D model

Introduction

Archaeology is well known as a field of enquiry devoted to studying cultures of the past through material remnants and traces of ancient civilizations. Among them there can appear remnants of architectural works, the analysis of which constitutes an important field of archaeology.

In many cases, these witnesses of the past served different purposes over the course of time, to mention, for example, the Pantheon in Rome that in the course of centuries has changed its function quite a number of times: it was a temple during the imperial epoch, a resting place for illustrious people — today, as in the past, it is a normally functioning church. In these cases it is possible to talk of proper architecture. Italian legislation classifies such a structure as a work of architecture and not of archaeology, while they also bear testimony to various cultures that adapted it to its exigencies in the course of centuries, and therefore are of interest both to the history of architecture and to archaeology.

Let us bear in mind, moreover, that one of the characteristic features of works of architecture — as opposed to other material testimonies — on the one hand is their considerable resistance to the destructive influence of time, which in many cases means tens of centuries. On the other hand, the fact of their serving various specific human activities through successive generations, transforms their edifices to suit new functions. As a result, works of architecture — for example those of imperial Rome, have undergone innumerable transformations, the traces of which can be more or less identified, and are to be found on the different surfaces, visible or hidden, of elements composing the building. The researchers can decode them with patient and painstaking analytical work.

By way of an example, an intervention of restoring or substituting a piece of a cornice can be said to be impressed in the material with which it was made and can be identified by expert eyes. Other causes of transformations appear beside the above modifying agents, such as catastrophes (earthquakes) or phenomena that take their source in the static behaviour of the edifice (structural caving in with subsequent damage).

Innumerable modifications imposed by new functional exigencies or by restoration interventions executed on historic architecture, or those that form sequences in buildings, can be analysed and studied by carefully surveying their wall structure. These modifications are subsequently represented in their internal and external surfaces, thus by achieving a proper check-up by the application of stratigraphic analysis of their wall structure, i.e. by an accurate representation of all visible and invisible parts of the artefact, these changes can be studied. In other words, there is a need for accurate and numerous representations of all the parts that can 'communicate' the artefact to us through its components. This takes us through its history, retracing the transformations of the work, until it is situated back in its original cultural climate in all its aspects.

It then becomes possible to reconstruct — ideally and also virtually — the initial project underlying the work of architecture. In order to transmit such a massive amount of information that can be extracted from an ancient artefact, the representation must provide all the information contained in its various component parts. This signifies that its drawings must be executed in various scales, so that all the information from which a minute analysis of various parts can be performed can be holistically collected (Benedetti *et al*., 2010; Bourke, 2012; Brunetaud *et al*., 2012).

In order to represent a structure like the Colosseum, it is necessary to discover and analyse the principles underlying its construction, bearing in mind the rules of geometry applied to trace an oval with four centres that delimits its perimeter and the whole planimetric layout. It also imposes an attempt at reconstructing the spatial positioning of the four centres applied to delineate the arches of circumference, much in the same way as it is necessary to interpret the delineation of the external perimeter through an analysis of signs left by Roman constructors and still visible on the base part built of travertine. We might continue to develop the subject ad infinitum, because surveying and representing an ancient artefact like the Colosseum means entering into syntony with the whole work. This is necessary in order to understand and describe the various construction techniques, bringing out the existing geometric relations between the planimetric layout and the elevation, and for describing various relations of proportion according to which the superimposed external orders were erected and, by the same token, describing the proportions of the whole edifice.

We believe, however, that in order to attain a deep knowledge of the architecture of ancient times, it is necessary to have at one's disposal a representation that will contain all the information ordinarily used by the architect-historian or a restorer and — at the same time — of the archaeologist. Recently these two professions have been getting closer to each other, ever since architects started to pay more attention to 'reading' or rather, interpreting buildings in all their aspects. Simultaneously, the archaeology of architecture has been gaining the status of a discipline in its own right, with its own characteristic features different from those of traditional archaeology. In our opinion the representation of archaeology and of architecture ought to become more complex than at present, in order to be able to represent all the 'readings' or interpretations attempted by architects and archaeologists, with the objective being to represent the complex range of information yielded by different interpretation typologies (Docci, 2007; Koutsoudis *et al*., 2014).

Technological innovations in surveying and representing archaeological architecture

The 21st century has witnessed the birth and consolidation of a new surveying method, performed with the laser scanner. Its peculiar feature is that it collects points off the archaeological-architectural artefact to be surveyed, creating a point cloud (a set of points in space on the surface of a work of architecture). The new technique made the operators transform the numerical model into a geometrical or a mathematical one; in other words into a virtual 3D model characterised by the continuity of its surfaces (Bianchini, 2012b). *Archaeological Architecture* (Molyneaux, 2011; Bianchini, 2012a) is constituted by a massive number of surfaces (planes, cones, cylinders, rotation surfaces, paraboloids, etc.), and hence the set of points extracted from a survey with a laser scanner must inevitably be transformed into continuous surfaces by the application of MESH or Non-Uniform Rational Basis Spline (NURBS) so that the researchers are certain they have surveyed all the characteristic points of the work analysed. Consequently, the transformation of the numerical model into a geometrical one, allows one to obtain the 3D representation of the object surveyed, a model that can then be elaborated in the way described in the successive part of the article (Ippolito *et al*., 2013; Carpiceci and Inglese, 2015).

The necessity of elaborating 3D models as a successive stage, make it possible to apply high definition images of the object surveyed on the model. In this way, high definition 3D models are obtained, which have, in recent years become basic outputs for surveys performed (Vrubel *et al*., 2009; Docci *et al*., 2011). When completed, the models can be used to produce the 2D representations necessary to achieve an exhaustive bi-dimensional representation by obtaining planes, sections and prospects of the represented work.

Currently available on the labour market are services which transform 3D models into bi-dimensional representations for representing either the present state of the work, or a possible representation of a restoration or transformation design if the designer realised the 3D model including the interventions planned. Today, surveying with laser scanners or through image based modelling, we can elaborate digital 3D models of ancient artefacts. Then, by spreading super high definition photographs on these models, we can obtain hyper realistic models to be used in various ways (Docci, 2012; Remondino and Campana, 2014). On precisely such models we can carry out initial analyses of the state of preservation of surfaces, map out the degree of their degradation, and identify changes in the wall texture, while in case of decorative coverings, gaps can be discovered. When cracks are found, it is possible to enlarge them in order to find out if their edges are flat, or it is possible to represent the spatial (three dimensional) layout of the crack to understand its cause. The 3D model opens up the possibility for a thematic elaboration, as for example to register (report) wall stratigraphy of delimited portions of surfaces (e.g. 15 × 15 cm).

The 3D model can be transformed into a series of 2D representations, e.g. planes, prospects, or sections in numerous points of the edifice. In this way a two dimensional representation is obtained corresponding to the usual design graphics, but on which one can elaborate many other thematic analyses, like metrological or proportional research. It is common knowledge that analyses of proportions must be carried out by applying the unit of measurement used for constructing the building (Inglese, 2000, 2013). Enquiries into what unit of measurement was used for building an edifice can be considerably facilitated by applying an adjuster, which can help convert modern meters into ancient ones. These are known to vary a little, as it was demonstrated by the surveys of the Colosseum. Also from this point of view it can be seen that new technologies help to rapidly select a proper solution.

In recent years, a research group of the former RADAAr Department — today's Department of History, Drawing and Restoration of Architecture — has carried out surveys and worked out representations of various historical buildings, all of which fall into the category of 'archaeological architecture', applying the criteria described above.

In the pages to follow, we shall present three cases of symbolic significance, all related to ancient Roman archaeological architecture: the Arch of Janus, the Pantheon and the Colosseum, all located in Rome.

The Janus Arch

The so-called Arch of Janus (Figure 1) is a well-preserved quadrifons arch in Rome, and has several unique archaeological and architectural characteristics[1]. The building process is very complex, and several details of the construction and finish of the building materials would have remained undetected without a high precision survey. Due to the arch's location and its important role in the topography and urban planning of the Forum Boarium, it underwent extensive changes over the years, even though its overall appearance remains unaltered in those areas where its structure is intact. These changes include: the destruction of some parts of the foundation and attic; additional structures inside and outside the arch, and also along the upper part made during the Middle Ages by the Frangipane family; the neglect and demolition of the parts built during the Middle Ages; the extensive modern renovations, and the closure of the adjacent area after the terrorist attack in the 1990s.

Figure 1. The Arch of Janus in Rome (photo by authors).

To correctly establish an operational protocol,[2] the survey concept has to be properly identified and this involves merging two separate kinds of survey: *critical survey*, which defines the object using its geometric and architectural characteristics, and *objective survey* which consists in ensuring unbiased data to allow for an in-depth specialist interpretation (Bianchini, *et al*., 2014a; Ippolito, 2015).

The survey will therefore depend on two consequential but inevitable aspects: *complex 3D surveying* achieved by using a combination of different tools, and *complex 3D survey* achieved by combining different models.

The *complex 3D surveying* involves acquiring the data and collecting any useful information about the object which can also be studied to acquire greater understanding and knowledge: an analytical phase focusing on collecting qualitative and quantitative data. A combination of methodologies and tools are used during the acquisition process including topography, image matching photography, and long and short range scanners.

The second step, the *complex 3D survey,* involves turning the 3D surveying into a 3D survey by *combining the models*, turning objective data (surveying) into data

[1] It stands near the church of San Giorgio al Velabro, not far from the Temple of Hercules and the Temple of Portunus, and was built on the edge of the Forum Boarium, probably in the mid-fourth century. It presumably coincides with the Arcus Divi Constantini, mentioned in the Regionary Catalogues near the Velabro. Like the corridors present in the spas in the Roman Forum, it wasn't a triumphal arch, but probably a building used by the bankers working in the Forum Boarium. The square plan building (12 m each side, 16 m high) had four massive cement pillars covered in old reused marble and supporting a cross vault.

[2] This study was carried out with archaeologists of the Instituto Arquelogìa de Mérida, Spain.

containing all the information required to interpret and study the building (survey).

In the digital age, the model concept is based on digital techniques now present in all architectural representation tools, techniques which have also invaded the field of architectural survey. In particular, with regard to the model, 2D and 3D representations have created a new kind of model no longer only static, but also dynamic. The model concept must therefore be redefined and updated. This model is able to represent, comprehend, elaborate and modify the survey; it allows us to move around it and shift from outside to inside the model using the 2D and 3D elaborations in a transitive manner (Bianchini *et al.*, 2014b). A complex and absolute interactivity has been created between the real object (point clouds and photographs) and virtual system of digital models (2D and 3D models) capable of creating multilevel analytical documentation. This documentation is created by the systematic integration of the models defining and describing the object. The 2D and 3D models are characterised by geometry, topology and texture.

Considered in the Greek sense, geometry identifies the positions, i.e. the coordinates of the characteristic points defining the objects in space. Topology is considered as the definition and description of the relationships and links between the geometric entities, i.e., the study of forms. Texture is considered as a defining feature which, when applied to geometry and topology, determines the specific properties of the surface in order to make it recognisable and related to the original. So, on the one hand, geometry and topology define the object's geometric features and, on the other, texture characterises the former two using 2D and 3D patterns and maps.

Once the object's features have been defined, it's necessary to establish tools and procedure for the surveying and the way in which the models have to represent the object on different scales.

The data acquisition is carried out using the potential provided by tools such as theodolites, 3D laser scanners and high resolution cameras. Our extensive knowledge of different surveying techniques, acquired and tested in other studies, allowed us to combine the different technologies to obtain a point cloud - the objective numerical model.[3] It was necessary to perform both a topographic survey and another survey using a 3D laser scanner (Leica HDS 3000) because they were compatible and they would be more accurate when registering the various point clouds (in this case, registration error was less than 3 mm). Once this stage — acquisition, registration, and 'cleaning' of the data — was completed, the general point cloud consisted of 23,700,000 units. Because we obtained such extensive information from the survey campaign, we had to break down the architectural object into several parts so as to work with smaller point clouds, and therefore tackled assembly only during the final stages of the study.

The 3D models are also illustrated by geometric representation, proportioning and texture. In this case too, 2D models are developed by creating horizontal and vertical sections. Definition of the architectural features is determined using 2D maps and architectural representations. The 2D models are defined using drawings of the geometric representation, proportioning and architectural representation. These representations are developed after registering the point clouds, and the introduction of horizontal and vertical section planes. The points and lines defining the object are created by positioning the cloud itself in parallel projections, after which the operator will select its characteristic features.

To create 2D representations, i.e. plans, elevations and sections, we took several sections from the final 3D mesh model and compared them to sections obtained directly from the point cloud. This enabled us to verify how reliable the 3D model was: the difference between the latter and the point cloud was only a few millimetres and could therefore be used to create geometric 2D restitutions of the architectural object.

The mesh models provided a series of sections and cross-sections we used to create 2D images (plans, elevations and geometric sections). This was possible due to our architectural and archaeological knowledge of the Arch, which allowed us to identify individual parts, verify their proportions and the intrinsic rules governing them, and then draw them accurately.

To develop 2D and 3D scale models we also limited the amount of data we used by a tenth, thereby creating 3D models with a level of detail in line with their scale of representation (Apollonio *et al.*, 2011, 2013). This allowed us to create different scale 3D models, ranging from 1:200 to more detailed 1:2 scale models[4] (Figure 2).

[3] Synthetises of survey datum in which is registered every single information point acquired, be it metric or chromatic. The term refers to a model whose shape is described by points characterised by their spatial coordinates x, y, z, also known as point cloud characterised by greater speed in the phases of acquisition and elaboration of data. It makes possible the visualization of a 3D object in a computer. Naturally, this is just a piece of documentary data and it can in no way be considered a survey, but just a useful tool with which to begin working.

[4] This is part of a PhD thesis and of recent studies on the engraved traces on ancient buildings (Inglese, 2000, 2012, 2013; Inglese and Pizzo, 2014, 2016). The described procedure has been used for the construction of 2D/3D models of the Pantheon and Colosseum presented below.

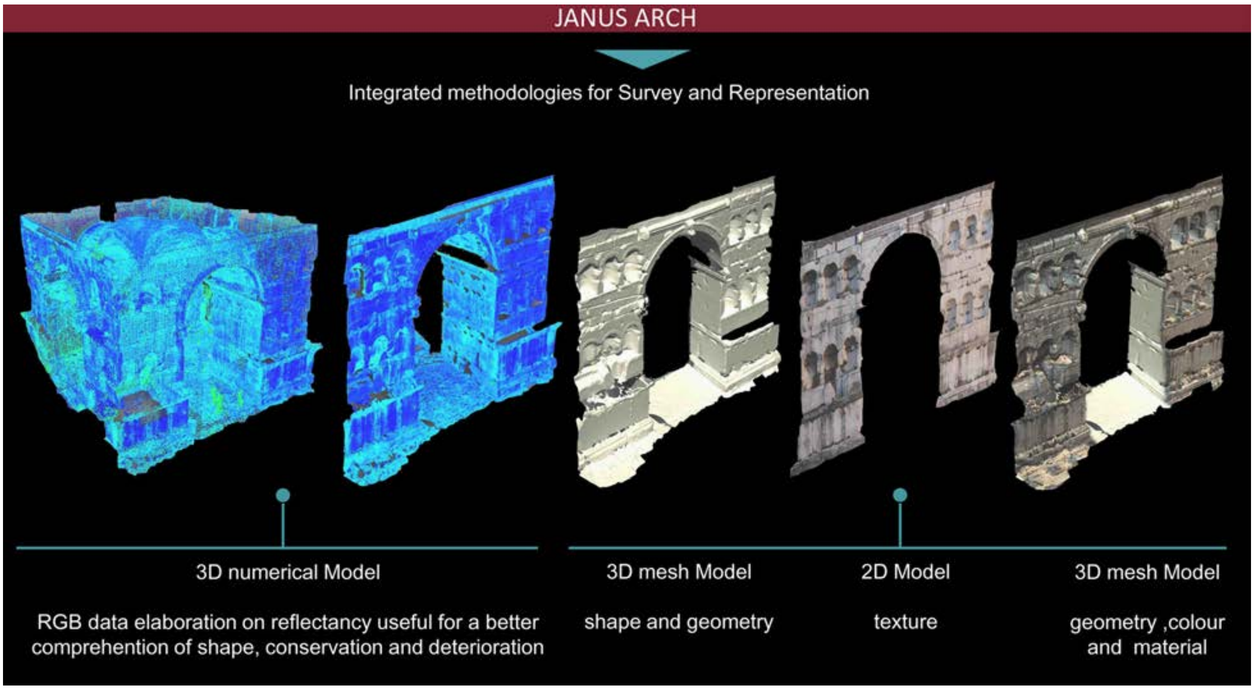

Figure 2. The Arch of Janus in Rome: integrated methodologies for survey and representation.

The Pantheon

The main aim is to discuss the advantages of a non-contact digital-catching in the study, documentation and analyses of archaeological contexts (Ippolito, 2015).

When working with complex structures, the integration of surveying methods has proven to be necessary, and can now be considered standard practice. It is thanks to this integration that we are capable of understanding the object of study and analysis, in both general and detailed terms. Surveying is thus to be intended as a rigorous methodological process that, through selection operations, measurement, and representation of important points, is capable of describing the geometric-spatial, dimensional, and formal qualities of the object of study. This process, in absolute, allows for the achievement of a profound awareness of the aforementioned object.

The integrated surveying of the pronaos of the Pantheon (Figure 3) made it possible to further verify the theory that the tracing lines engraved on the paving at the entrance of the Mausoleum of Augustus, are the final plans for the tympanum of the Pantheon. This interpretation is also corroborated by the studies of Lothar Haselberger on numerous worksite tracing lines representing the design of architectural details, 1:1 scale, used to control the building process. Representation, in this case, allowed us to establish a relationship between the Pantheon direct survey engravings and indirect survey of the pronaos. The role of the representation is fundamental for the construction of one of the most important buildings from antiquity. This allows us to understand the history and all the construction aspects (Inglese and Pizzo, 2014, 2016).

The metric and formal data regarding the plans were obtained during a direct survey campaign conducted in 1999, before the start of excavation conducted by Archaeological Superintendence, the authority which currently grants access to the area of the Mausoleum of Augustus. The engraving and supporting travertine slabs were measured directly in situ; the thickness of engravings (on average just half a centimetre) was measured using a crack meter. This direct measurement campaign provided us with the size and formal characteristics of the engravings, as well as the reciprocal position of the elements in the plan. The engravings are partly covered by a modern curtailment wall. These are the measurements of the major tympanum with the tripartite division of classical trabeation, as measured by the 1999 direct survey: length of horizontal elements 6.42 m; height of the tripartite fascia 2.05 m; length of the sloping elements, 7.15 m, with a roughly 24° gradient. A fascia approximately 0.60 m high is located below the cornice; when it reaches the frieze it has several short vertical elements emphasised by circumference placed at a reciprocal distance of 0.045 m; the latter representing the inter-axes of the column of an octastile façade. The horizontal elements of the smaller tympanum are more schematic compared to the other, and measure

Figure 3. The Pantheon in Rome: internal view of the dome (photo by authors).

approximately 6.42 m; the axes of symmetry are 4.15 m long; the gradient is 21°.

A little over ten years later we repeated a similar survey of the tympanum of the Pantheon with a 3D Laser scanner, and then superimposed the graphic restitution of the engravings on the point cloud (Figure 4). Above all, it allowed us to test the use of the laser scanner survey method in a comparative study of the worksite by tracing lines of the architectural elements and the actual architectural elements (Inglese, 2012). Having conducted a meticulous preparatory logistic analysis of the monument and its surroundings, we developed a survey project requiring the use of two different methodologies: topography and a 3D laser scanner survey (Figure 5). The instrumental survey, which used an integrated station and an open polygon, was considered merely as a support for the next scan. This kind of survey allowed us to rigidly block the surveyed object and to use the survey to support and verify all the further scans made with the 3D laser scanner.[5]

This survey produced an objective numeric model of the façade of Pantheon, and was also the first data we could use to check Haselberger's theory. The necessary elaborations, in essence an orthogonal projection of the façade, are based on this metadata. Two types of scans are used: a general scan with 5 × 5 mm sample spacing to acquire the entire complex or large parts of it, and a detailed scan with 2 × 2 mm sample spacing for the target. The final result is a numerical model with uncertainty detail under 3 mm. It is compatible with the goal of the survey and the representation scale that was previously established in 1:50.

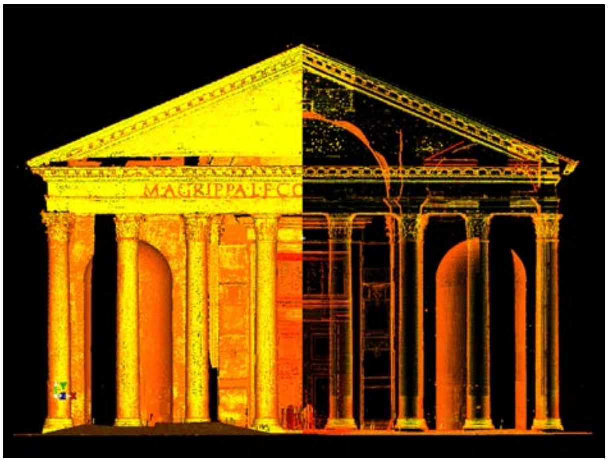

Figure 4. The Pantheon in Rome: Reflectance visualization of pronaos façade. Survey by Priscilla Paolini, elaboration by Carlo Inglese.

Figure 5. The Pantheon in Rome: Reflectance visualization of pronaos façade. Detail. Survey by Priscilla Paolini, elaboration by Carlo Inglese.

The direct survey of the engravings was superimposed on the parallel projection of the point cloud, to create an outline of the façade with sharp features. This

[5] The integrated survey was conducted using a Leica Total Station TCR 1201 R300 and the scanner laser Leica C10.

Figure 6. The Colosseum.

verification resulted in substantial correspondence between the plan of the major tympanum and the architectural elements of Pantheon. This elaboration only involves the position of the pronaos and the vertical and inclined consoles of the cornice.

Furthermore — and this is one of the most interesting aspects of this study — if the current archaeological excavation campaign unearths more engravings, or supplementary parts of the one we already have, then the numerical model obtained can be used again and new data simply added.

The Colosseum

The study of the Colosseum (Docci, 2002) has, for years, involved survey and representation activities from our department, previously RADAAr (Department of Survey, Analysis and Representation of the Environment and Architecture) and today DSDRA (Department of History, Representation and Restoration of Architecture) (Figure 6). The study, which began in 1998 with an integrated survey, topographic, photogrammetry and direct, is now optimised through the use of massive acquisition methods (3D laser scanning and Gigaphoto) (Baglioni and Inglese, 2015).

In the first stage, a 3D long range laser scanner as a total station was used; establishing the spatial coordinates of every station to create polygons based on the station points, and as a result, obtaining the georeferenced point cloud (Figure 7). This operation produced surplus data (the topographic network itself was a sufficiently reliable grid during registration of each cloud) but it also kept the mean error to roughly 1 mm. The general 2D drawings were obtained from the numerical model thanks to the homological recognition of the targets that took place during the preparatory registration of the single point clouds. The second stage of the survey involved the in-depth study and integration of the data obtained during acquisition and restitution; we went on to acquire the high resolution panoramic images we needed to perform a thorough study of the building (Figure 8).

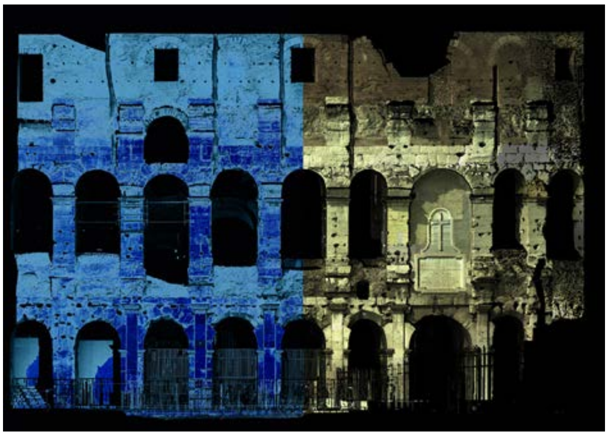

Figure 7. The Colosseum: reflectance visualization of fornix with true colors.

The high resolution panoramic images, commonly known as Gigapixel,[6] were created using a camera with a full-frame sensor mounted on a motorised panoramic head. As regards to the images, we used the integrated tools in the stitching programmes and the surveyed topographic data[7] to identify the position of the main plane of each elevation (with an approximation of 10 cm); this allowed us to perform image rectification on a 1:10 scale with a resolution of 300 dpi, integrated into the drawings made during this stage. The 1:10

[6] Nikon D800 full frame digital camera (3.2 Megapixel sensor) with a Nikon AF 200 mm f/4 D ED IF Micro lens mounted on a Gigapan Epic Pro motorised panoramic head.

[7] The topographic reading was used to correctly place the position of the orthoplanes from the high resolution photographs. The topographic points, taken on several specific reference planes, materialise the position of the planes themselves; these points, in turn pinpointed on the giga-photo, correctly materialise the rectified plane on the photograph.

Figure 8. The Colosseum: gigaphoto of fornix XVII (elaboration by Leonardo Baglioni).

scale caused a considerable loss of data of the original Gigapixel images (on average, roughly 1:6 at 300 dpi).[8] To make these panoramic images more navigable and, more in general, to turn them into a tool to analyse the building (since they are always true form rather than full size rectifications) we used a technique that generated pyramidal images from the original Gigapixel image (Figure 9).

Conclusions

The potential offered by the use of new survey tools for massive data acquisition of points, as 3D laser scanner or Gigapixels images, allows us to study the depth characteristic aspects of the artefacts, with a level of detail and a resolution that was an unimaginable up until a few years ago.

In particular, the Gigapixels image rectification allows us to implement the classic 2D/3D models built in the process of restitution. These 2D/3D data provide an important support for new data analysis, new data readings, or restoration, which are based on different interpretations.

The archaeological architectural representation process now is at the centre of a transformation related to survey technologies, which in recent years has become more and more developed. The use of new survey tools allows us to recognise how the geometric survey process is more and more consolidated (Gaiani *et al*., 2011; Bianchini *et al*., 2015b).

The 2D geometric models that point out the formal features of the buildings, today can be integrated with new highly geometrically and metrically accurate data deriving from Gigapixels image.

The 2D architectural representation has always been characterised by a high degree of subjectivity. In fact, it is linked to the ability and the operator's sensitivity to recognise and represent the main characters of the analysed elements. Now the 2D/3D representation is highly implemented, sometimes almost replaced, by the objective construction of the archaeological-architectural characters of the studied artefacts (Bianchini *et al*., 2015a).

[8] The north façade is represented by a Gigapixel made up of 96 shots providing a 35% overlap. The shots were taken at a distance of roughly 12 metres from the main façade using ISO 100, f16 (so as to generate a depth of field between 12.7 m and 18.2 m, calculated at a focal distance of 15 m) with a 1/4" exposure. Diffuse lighting meant that the HDRI technique was not necessary. The west façade is made up of 132 photographs taken at a distance of roughly 20 m with ISO 100, f16 (depth of field from 19.3 m to 35.6 m with a focal distance of 25 m) and a 1/15" exposure. This façade, with its very varied projecting parts and recesses required 4 different photo-rectifications, each suitably reduced on a 1:10 scale. Here too, diffuse light meant that the HDRI technique was not required. The Gigapixel image of the east façade was generated from a centre of projection on the first floor of the convent next to the church at a distance of roughly 10 metres; it is made up of 117 photographs with a 35% superimposition.

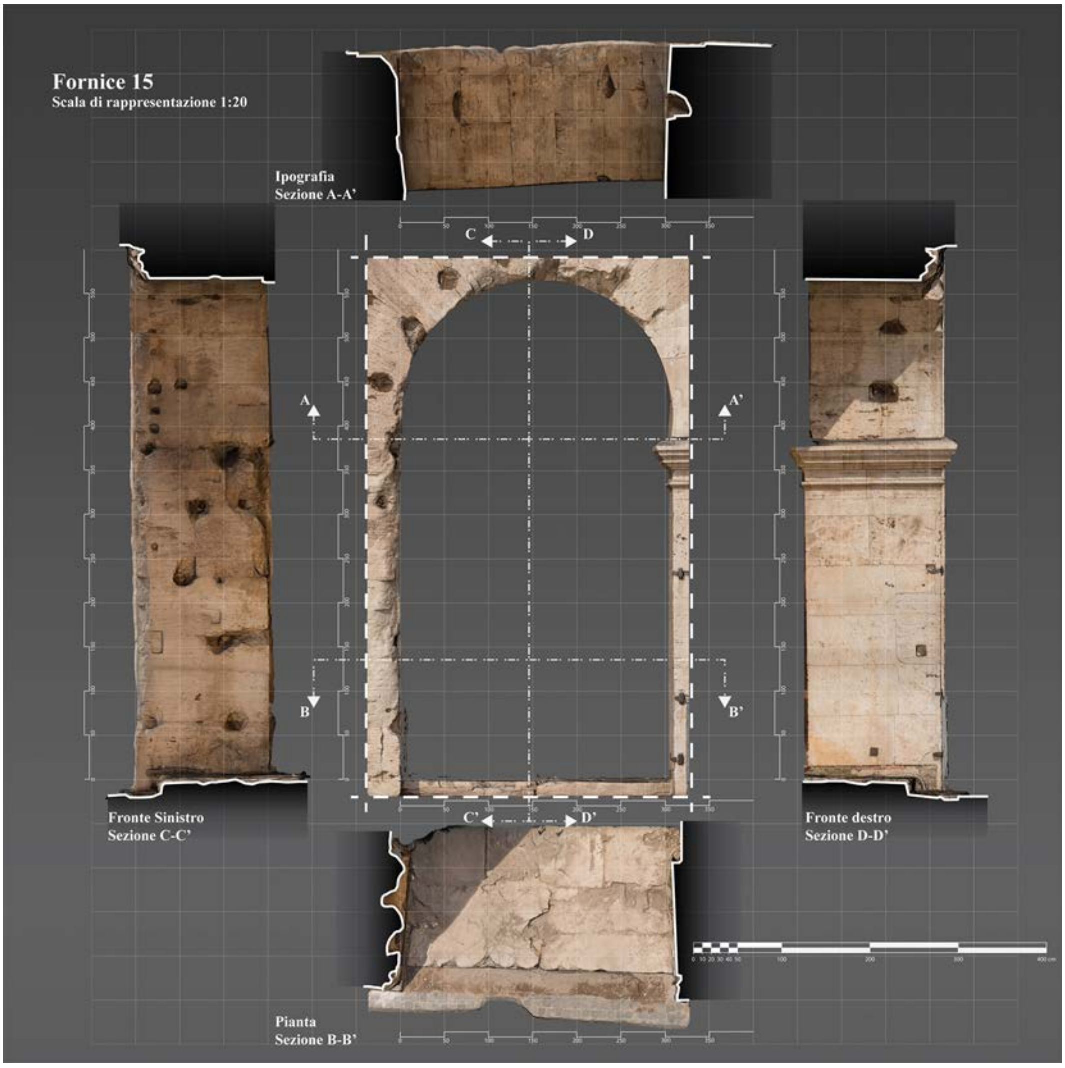

Figure 9. The Colosseum: orthographic view from Gigaphoto (elaboration by Leonardo Baglioni).

The representation of the archaeological-architectural survey now is one of the most dynamic moments thanks to the developments in the acquisition and restitution process of survey data.

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Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
Oxford: Archaeopress

Digital Archaeological Dissemination: Eleniana Domus in Rome

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Abstract

This research is based on the virtual reconstruction and enhanced communication of the Eleniana Domus using the New Technologies (NNTT).

The historical interest of the site, along with its excellent state of preservation and the works that turned it into a museum, make the Domus an excellent subject to develop innovative research with virtual reconstruction and interactive applications directly on site.

The methodology underlying the research involves a series of mutually connected activities:

- survey of the object or area of interest by means of a 3D laser scan;
- implementation and management of a 3D mesh model obtained by points cloud;
- 3D model processing as a function of the different display modes;
- projection mapping presentation;
- provision of a mode of interaction where visitors choose the type of information and insights that they wish to receive.

Keywords: interaction, 3D modeling, 3D simulation, Augmented Reality

Introduction

The area of Santa Croce in Gerusalemme is home to an impressive archaeological complex, located behind the Aurelian Walls. Here, there are the remains of the imperial residence of the Severi, which was built between the end of the 2nd and the beginning of the 3rd century AD. The area of the villa is made up of various monuments and is surrounded by a large garden. It also contains the ruins of the Castrense Amphitheatre. Most likely, it was built by the Emperor Heliogabalus (218–222 AD) as the amphitheatre of the court adjacent to the Imperial Residence. The amphitheatre is entirely built by bricklaying and had a capacity of approximately 3,500 spectators. It is the only one still preserved in Rome, in addition to the Colosseum.

In this archaeological area, one can visit the Varian Circus (577 m long) and some of its remaining rooms, close to the Cloister of Santa Croce in Gerusalemme. The imperial palace was expanded in the 4th century AD upon Constantine and his mother Elena's orders (Figure 1). Today, one can still see parts of the background wall and of the huge apse that represented the civil basilica, called 'The Temple of Venus and Cupidine', and a number of *domus* that were probably inhabited by the Court dignitaries. Here, black and white mosaic floors with the portraits of the hosts have been found.

One can also visit the section that has been excavated since 1982: it is a house from the imperial age, attributed to Aufidia Valentilla, with remnants of wall frescoes, called Eleniana *Domus* (Borgia *et al.*, 2008).

Related works

Some projects have been implemented in Italy to allow visitors to experience archaeological areas in new ways, made possible by the latest multimedia and interactive technologies.

Among these, the following are relevant for the purposes of the research:

- *Roman Domus* at Palazzo Valentini in Rome;
- Exhibition 'Forum of Augustus. 2000 years ago', Imperial Fora of Rome;
- Exhibition 'Journeys into Ancient Rome', Imperial Fora of Rome.

The Roman D*omus* located beneath Palazzo Valentini (built in 1585) in Rome is an example of the restoration and redevelopment of artistic heritage, enhanced through the use of new technologies as a result of a project carried out in 2010.

The enhancement was curated by Piero Angela and a group of technicians and experts, including Paco Lanciano and Gaetano Capasso. The project, through virtual reconstructions and multimedia effects, has enabled the reconstruction of the mosaics, decorated walls, polychrome floors, basalts and other artefacts

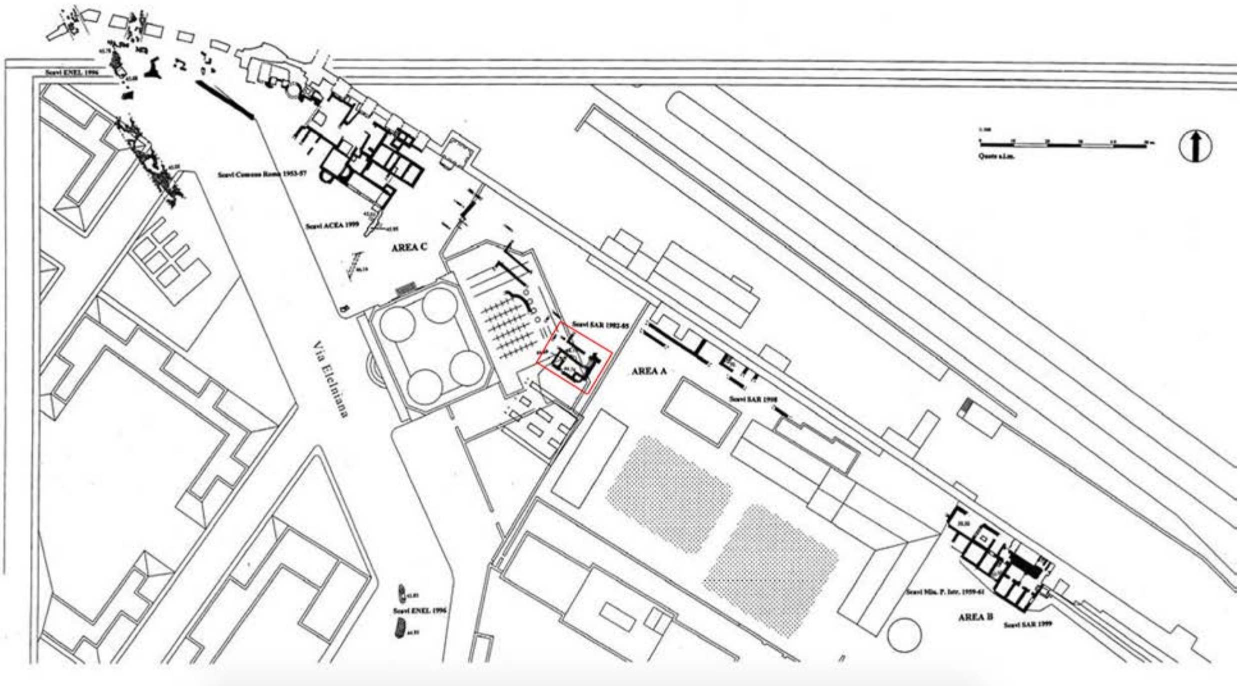

Figure 1. Archaeological area — Sessorium Palace IV sec. b.C., Constantine Age. Eleniana domus position is boxed (image processed by E. Borgia and D. Colli).

present in the patrician Domus of imperial age, located beneath Palazzo Valentini.

Celebrations for the bi-millenary of Augustus's death (19th of August, 14 AD) helped valorise the Imperial Fora with the exhibition 'Forum of Augustus. 2000 years ago', from April 22 to October 21, 2014 (Ministero dei Beni e delle Attività Culturali e del Turismo, years 2014, 2015, 2016). Here, the communication tool was a multimedia installation with a projection on the walls of the Forum of Augustus, representing the history of Augustus and the Forum with lights, films and projection mapping reconstructions.

The success of the 2014 exhibition 'The Forum of Augustus. 2000 years later, led to the organisation of 'Journeys into Ancient Rome' (Viaggio nei Fori, years 2015 and 2016). Reconstructions and videos take visitors back through the history of the excavations carried out to build Via dei Fori Imperiali, when an army of 1,500 construction workers, labourers and other workers were enlisted in an operation unlike any before, razing an entire neighbourhood to the ground and digging down to ancient Roman street levels.

The exhibition went further back into the story, starting with the remains of the impressive Temple of Venus, whose construction was ordered by Julius Caesar after his victory over Pompey, reliving the emotional experience of life in Roman times, when officials, commoners, soldiers, matrons, consuls and senators walked beneath the arches of the Forum. Among the remaining colonnades can be seen the *tabernae*, which were offices and shops and, among these, a *nummularius*, a kind of currency exchange office. There was also a large public lavatory, some of whose remains are still in existence.

The tour tried to recapture the role of the Forum in the life of Romans, as well as the figure of Julius Caesar. To build this great public work, Caesar expropriated and demolished an entire neighbourhood and the overall cost was 100 million aurei, the equivalent today of at least 300 million Euros. He also wanted the new home of the Roman Senate, the Curia, to be built right next to his Forum. The Curia still exists, and virtual reconstructions show us what it looked like in Roman times.

Eleniana Domus

The brickwork structures of the Eleniana *domus* (Aufidia Valentilla domus) were first discovered in 1982, as workers were laying electrical cables inside the ACEA site of via Eleniana. Larger excavations have since been conducted, between November 1984 and May 1985 (Borgia *et al.*, 2008) (Figure 2).

The *domus* features luxurious pictorial decorations, probably dating to the turn of the 2nd century.

Figure 2. Restoration, 1985.

Figure 3. Restoration, 2007.

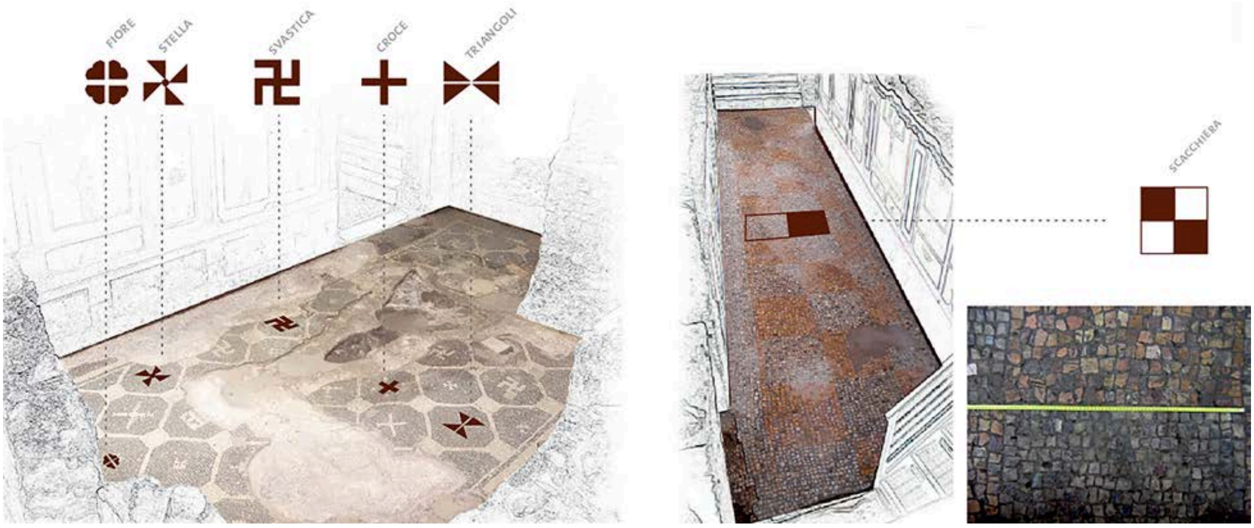

Figure 4. Mosaics in the corridor and triclinium (image processed by F. D'Antonio, A. Rastelli, and M.P. Scialla).

Moreover, signs of restorations made in the beginning of the 4th century AD are still visible. The walls are made of *opus caementicium* with an outer tile covering made of tufa *opus reticulatum*, sometimes arranged irregularly, with interconnected bricks of *opus latericium*. Two main environments are visible in the *domus*: a corridor and a *triclinium*. The *Triclinium* is surrounded by decorated walls made of *opus reticulatum*. A central corridor paved with a mosaic made of large marble tiles leads to two side rooms, located to the south–west. The last restoration included a structure to protect the site against atmospheric agents and was completed in 2007 (Figure 3).

The central corridor

The central corridor leads to two side rooms; the one located south–west was especially excavated and has the shape of a *triclinium*.

The corridor is paved with a mosaic made up of large marble tiles (Figure 4); they form a decoration with alternating yellow and grey-light blue large squares. The walls, above a baseboard covered with dark red plaster, exhibit a pictorial decoration consisting of panels with small squares inside, with portraits of both women and men.

The Triclinium

The *Triclinium* has walls with paintings. On the north/east wall, quite well preserved, one can notice above a high baseboard filled with dark red, the frescoes of a peacock and a ruminant, perhaps a sheep; at the centre of two panels, a rampant ibex and a bird with its open wings are also portrayed. Two columns frame a third panel with a female figure in the middle, wearing draped cloths; her right hand leans forward as a sign of invitation. Another pair of columns frames two more panels where a man and a woman have been depicted. The short north/west wall exhibits a single panel representing a female figure. The floor is composed of a mosaic with black and white tiles, arranged in geometric decorations with lozenges, crosses, swastikas, stars and stylized flowers (Figure 4).

From here, one can enter another small room with a wall decoration consisting of white panels with yellow frames and verses separated by red lines. Again, two figures, a male and a female, are visible on the walls of a room on the opposite side of the corridor; now the object of a minor excavation.

All decorations present on the walls of the visible rooms of the *domus* seem to date back to a single restructuring of the house during the Severian age, with restoration works dating back to the early 4th century AD. The presence of other floor levels under the corridor and the *triclinium* reveals an age preceding the Severi period (Borgia *et al.*, 2008).

Research

The purpose of the research carried out by the Laboratory of Visual and Digital Studies in Architecture of the Department of History, Representation and Restoration in Architecture — Sapienza University of Rome and the Superintendency for the Colosseum, MNR and the Archaeological Area of Rome, is a virtual reconstruction and enhanced communication of the *Domus* Eleniana. While the latter is largely unknown to scholars and tourists, new technologies can help disseminate information about it.

The historical interest of the site, along with its excellent state of preservation and the works that turned it into a museum, make the Domus an excellent subject to develop innovative research with virtual reconstruction and interactive applications directly on site. A 3D laser scan, the subsequent reconstruction of the textured 3D model, *real time* views both on a desktop computer and on *portable devices*, multimedia and interactivity allow us to better understand the history and construction techniques of the *domus*.

The methodology consists of a series of mutually connected steps:

(a) Data collection

Data collection consists of a survey of the object or area of interest by means of a 3D laser scan and the generation of a point cloud. In this way, it is possible to obtain a 3D model that has a dual function: representing (self-reference) the object itself, while simultaneously using Cartesian coordinates (x, y, z) of each single point of the model to handle other interaction methods.

(b) Organising and studying data

This involved the implementation and management of a 3D *mesh* model resulting from the points cloud and processing of 3D model as a function for: display on *portable devices* (such as *smartphones* and *tablets*) in *Augmented Reality mode*; use of *projection mapping*; model navigation in *real time* on both computers and *portable devices*.

(c) Transforming data for dissemination

This focused upon the navigation of the 3D model textured in *real time* on a computer using Blender's internal *game engine*; *real time* navigation on *portable devices* through Unity; display on *portable devices* in *Augmented Reality mode* through the APP named 'Augmented'.

The *projection mapping* presentation of the floor and the main frescoed wall of *triclinium*, describing the evolution of the d*omus*, its construction techniques and materials proceeded the preparation of scenography to illustrate interactive information delimiting a suitable area (box, corner, wall), where *interaction design* tools are placed (overhead projector, 3D leap motion).

Data collection

The 3D laser scan was performed with a Leica C10, with five different shooting points: one in the corridor, one in the *triclinium*, one in the small room connected to the *triclinium* and two in the upper part of the area, from where it is possible to have an overall view of the place.[1]

In this way, there was generated a 2 Gb point cloud (Figure 5), and subsequently decimated with Cyclon software in order to realise a 3D model *mesh.* Geomagic Wrap allows the transformation of 3D scanning data into *meshes* of triangles.

Organising and studying data

The *mesh* obtained from the points cloud is then exported into an .obj interchange format before being imported into a 3D open source modelling program like Blender (Figure 6). Blender, thanks to the opportunities offered by its *tool*, allows an interesting series of subsequent steps; amongst others, it can generate a real time navigation of a 3D textured model reconstructing the appearance of the *domus* in the Roman period and as it looks now, thanks to the *game engine* inside the software running on a desktop computer.

From Blender, the 3D textured model is exported into 'Unity' for a real time navigation on *portable devices*, too.

[1] This part of the research was carried out with Carlo Inglese.

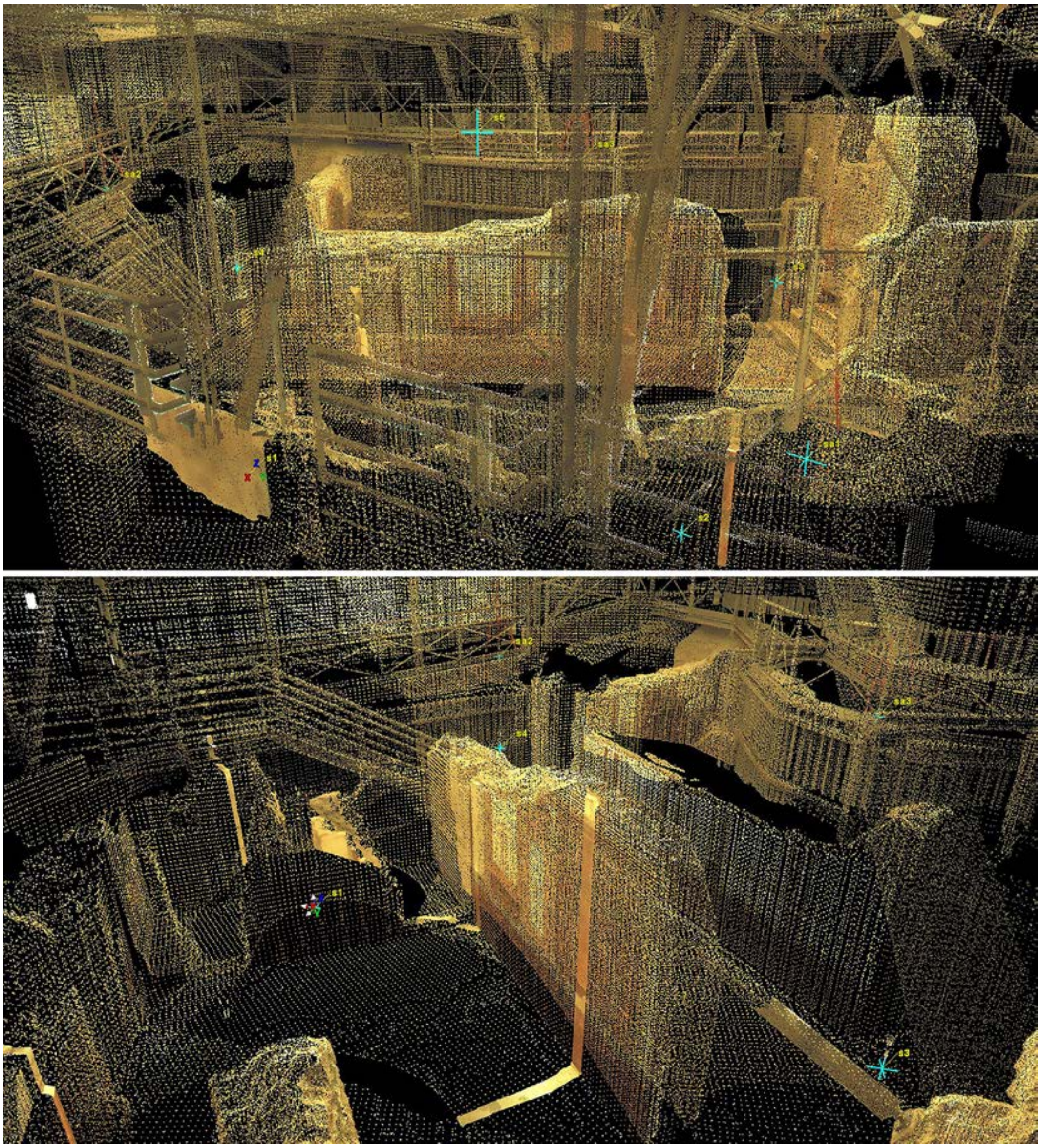

Figure 5. 3D laser scan points cloud.

As for *portable devices*, it is possible to realise a 3D model with a smaller number of polygons, so as to insert it into an app offering an *Augmented Reality* display mode through *ARTag*.

Transforming data for dissemination

Data and information regarding the *domus* can be transmitted in several ways: remote viewing, surfing the 3D model of the *domus* in a *virtual tour* both from a desktop computer and on mobile devices (*smartphones* and *tablets*) (Figure 7); direct display on site, via *projection mapping*, showing the evolution of the *Domus* and the construction techniques employed in its rooms, with special emphasis on the *triclinium*; realisation of a point of interaction, using 3D *leap motion,* where the user interacts with some elements present within the *domus*.

Real time virtual tour

The 3D modelling, starting from the points cloud, is performed with Blender (Empler, 2008), and is optimised for a real time navigation/display on desktop computer. To this end, some simplification procedures have been adopted:

- collision among simplified meshes;
- modelling of visible items only;
- replacing physical models with Alpha texture;
- simplified reflection (use of a texture with a pre-calculated reflection, thus not calculated during the real time tour by the computer);

The combined use of these options during modelling allows simplification of the real time computation. This makes the model seamless, without affecting its

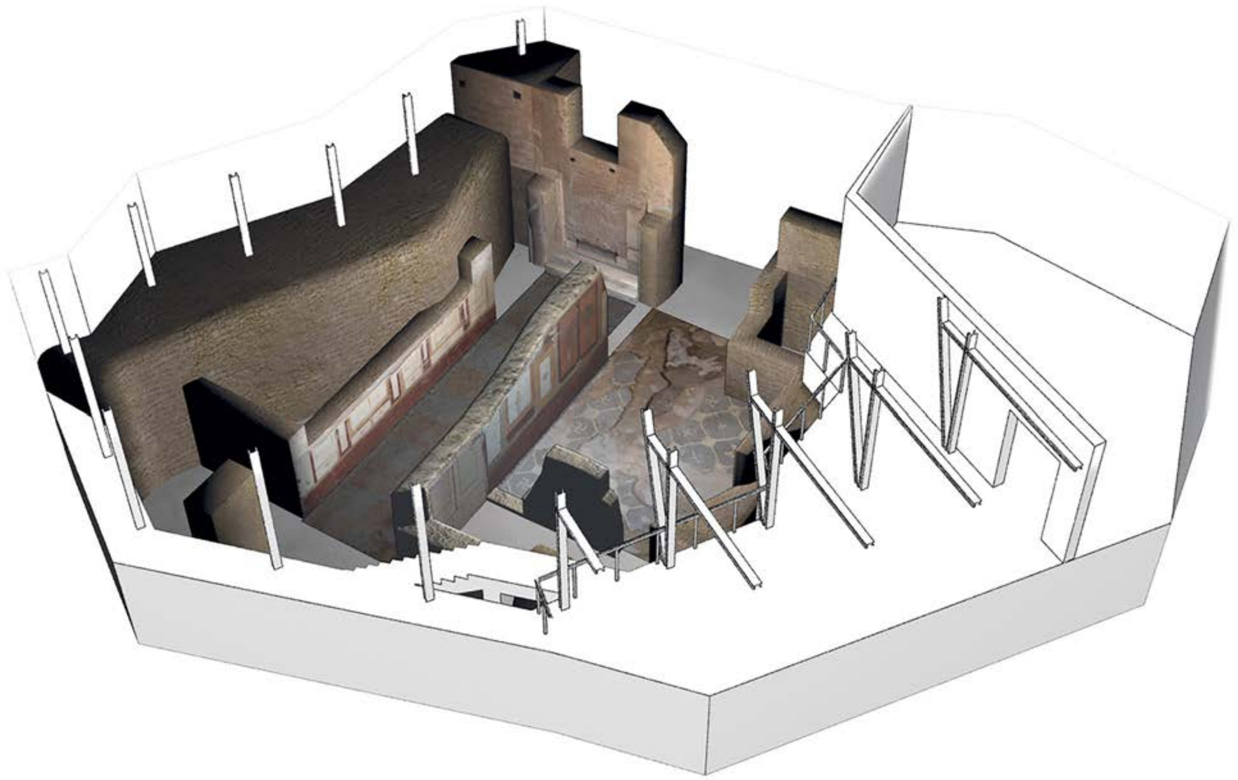

Figure 6. 3D mesh Modelling (image processed by F. D'Antonio, A. Rastelli, and M.P. Scialla).

Figure 7. 3D model with reconstruction of the different rooms (image processed by F. D'Antonio, A. Rastelli, M.P. Scialla).

aesthetic appearance. A simplified collision model with a limited number of vertices is created (*Low Poly* mesh) (Pescarin *et al.*, 2011).

Blender programming structure contains a 'game engine' (Empler *et al.*, 2016) which can simultaneously handle multiple events while enabling a real time visualization, such as:

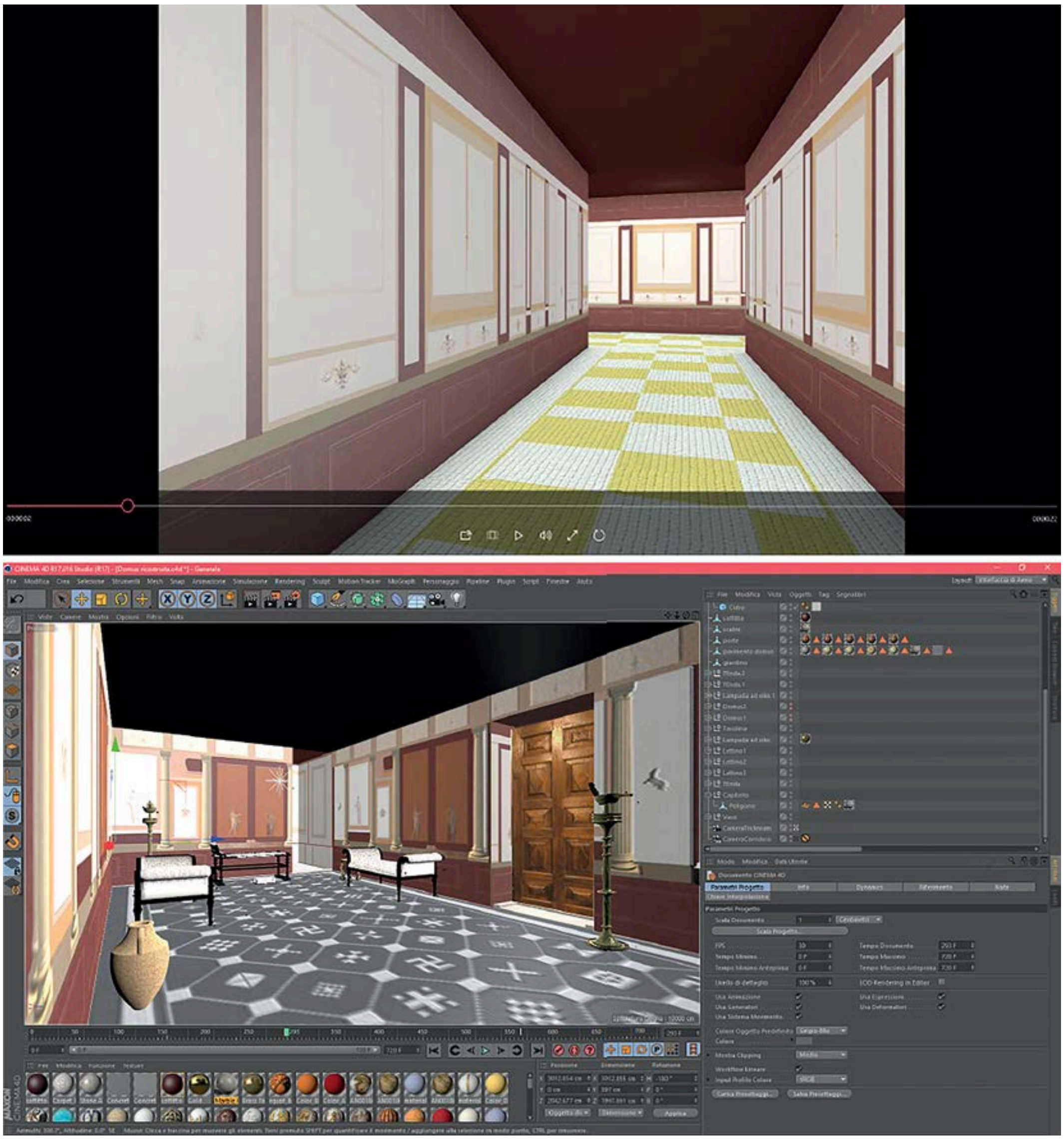

Figure 8. Real time virtual tour on PC (image processed by S. Bomben, A. Montesi, and I. Zappoli). Reconstruction supported by D. Colli (Borgia *et al.*, 2008).

- rendering of the scene with light effects and texturing;
- physical engine;
- management of sound events;
- management of the source code scripts;
- animations.

A combination of these features allows a simulation of the 'subjective' movement; individual images are produced in a short time, so as to have between 30 and 60 Frames Per Second (FPS), for a smooth motion display (Figure 8).

Viewing on *portable devices* can be obtained thanks to *Unity 3d*, a *real time engine* for three dimensional applications. *Unity* (Okita, 2015) is available with no licensing cost and can export applications for various devices from a single project. In this case, the project was first exported to a web version, then inserted on an online page and, thanks to the link with the *Android Development Kit*, even in a mobile phone Application (Figure 9).

Augmented Reality

Augmented Reality on mobile devices is based on ARTags (Murru *et al.*, 2013); once they are displayed by the camera, they are also recognised by the application launched on the smart device, where multimedia content is superimposed in real-time: video, audio, 3D objects. Each ARTag may be coupled to a certain amount of information; the application can, automatically and in real time, scan the tag itself, by identifying unique control points for each of them. In this specific case, the

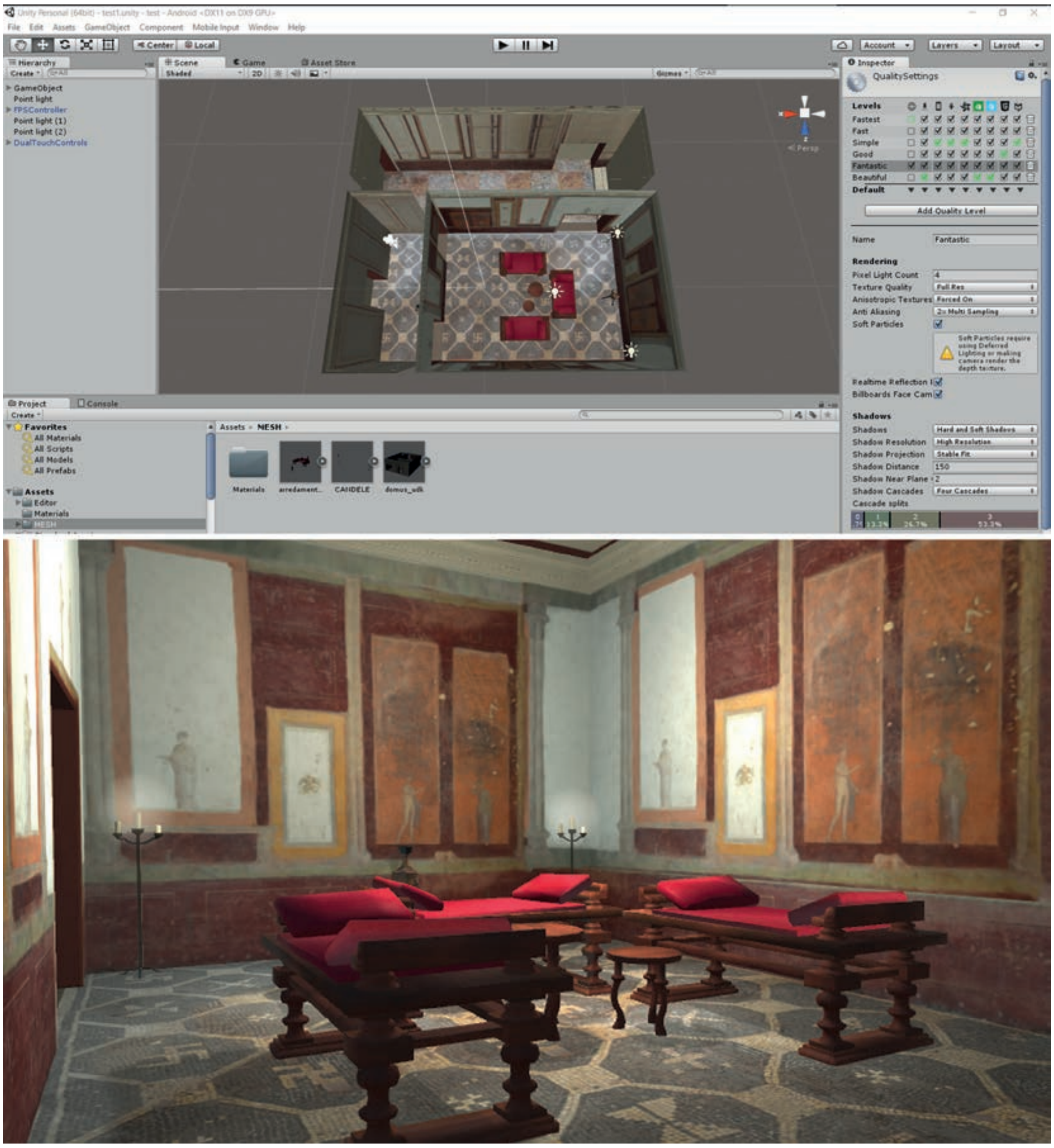

Figure 9. Real time virtual tour on portable devices by Unity (image processed by F. D'Antonio, A. Rastelli, M.P. Scialla).Reconstruction supported by D. Colli (Borgia *et al.*, 2008).

textured 3D model of the *domus* is reduced into polygons to allow an easier navigation. The model is displayed thanks to the Application named 'Augmented', which allows us to magnify, explore and photograph the three-dimensional model through different viewing options (Figure 10).

Projection Mapping

Projection Mapping uses the 'front projection' mode to animate, both in 3D and *motion graphic modes,* horizontal and vertical surfaces. First of all, it is necessary to 'map' the surface on which the projection must be carried out. It is necessary to detect all objects to be covered by the beam of light in order to allow a realistic interaction on each point of the scene, recognising the corners and shapes of objects. A specific software allows the animation to fully match with the mapped surface on which the projection is made (Maniello, 2015).

The screening of the video mapping in the area of the *triclinium* of *Domus Aufidiae* requires the use of two projectors (Figure 11), one for the pavement and a second one for the surface of the north/east wall. Given the particular shape of the cover made in 2007, it was necessary to devise a suitable junction system consisting of brackets with aliscaff hooks.

The two videos are shown simultaneously to allow the viewer to see how the environment appeared in the past.

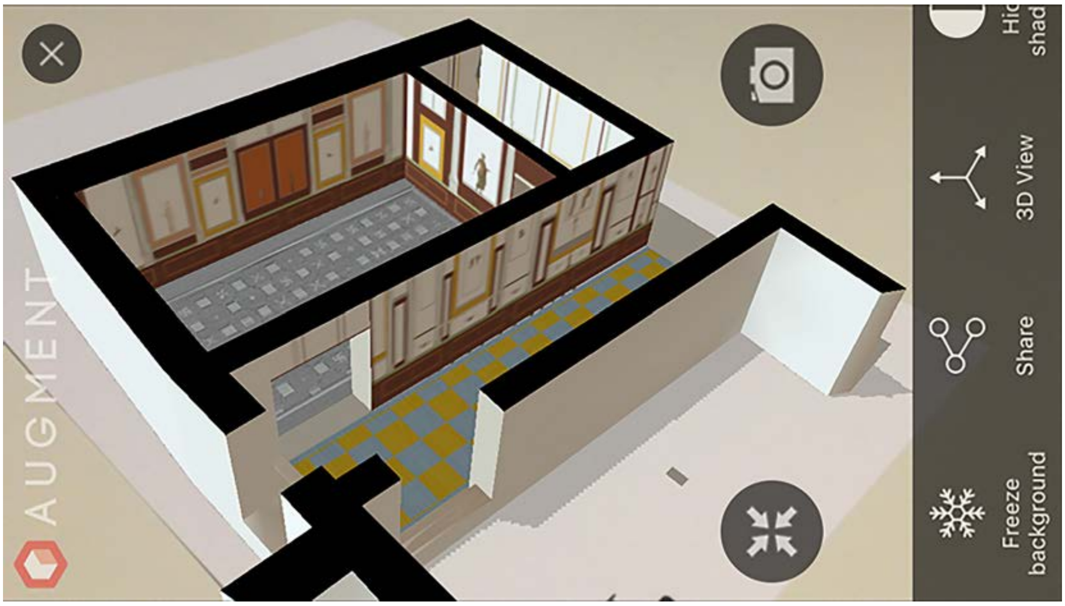

Figure 10. Augmented Reality on ARTag (image processed by F. Foti, M.G. Nocentini, and A. Testa).

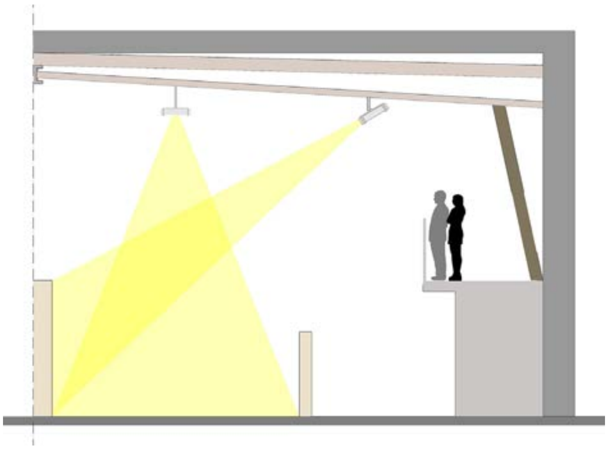

Figure 11. Section with the position of the video projectors (image processed by F. Foti, M.G. Nocentini, and A. Testa).

Video contents

The first video shows a reconstruction of the various pavement layers and mosaic. The second projection allows the reconstruction of the entire wall by filling in the missing parts of the fresco (Figure 12). Throughout the screening, the visitor is guided by a narrator emphasising the most important aspects shown in the video.

Video production technique

The two projections are made with an anaglyph technique. An anaglyph is a stereogram made of two superimposed images: the image on the left is characterised by red chromatic components whereas the image on the right has cyan chromatic components. The projection is formed by two parallel images, superimposed, filtered through coloured lenses in such a way that each eye sees only one of them. The binocular fusion allows the brain to combine the two images and perceive depth.

Interaction

From a frontal view with respect to the north/east wall, experiments are performed with a '3D leap motion' (Leap Motion, Inc., 2014), connected to a video projector, to obtain information on the frescoed wall and the floor of the *triclinium*. The 3D Leap Motion (Monaci, 2006) sensor can, through two IR cameras, return the spatial coordinates (in mm) of the hands and fingers that move within a given detectable area of approximately one cubic meter. The Software Development Kit (SDK), distributed with the sensor, arranges the coordinates (x, y, z) and vectors that describe the skeleton of the hand, in order to use its values with the main development platforms and tools: Unity, Unreal, Javascript, C++.

In order to virtually recreate the real location and shape of the objects so that they can be connected to data detected by the hand, a C++ software has been specially developed with the addition of SDK and open source Cinder++ libraries. This script defines the functions relating to the import of 3D models into the space of reference, event management, control of selections, and uploading and starting of multimedia files.

Figure 12. Projection mapping wall and mosaics (image processed by F. D'Antonio, A. Rastelli, and M.P. Scialla).

As a result of the experimentation with software and sensor, data on the hand and object (detected with the previously described method) are matched, provided that the following conditions are complied with:

- both must be expressed in the same scale (1:1) and unit of measurement (mm);
- the distance and the difference in height between the sensor and at least one point of the detected object must be known.

This allows the placement of everything in a space of reference having its origin (0, 0, 0) at the centre of the device.

Once the skeleton of the hand has been translated in the virtual space, thanks to Raycasting — often used in videogames programming — the application creates a dashed line led by the tip of the index finger according to the direction of the finger itself. The system then calculates the intersections of this 'radius' with the 3D elements present in the scene. In this way, it is possible to associate the occurrence of collisions with certain parts of the object and certain events, such as the playback of specific multimedia content. This causes the user to feel that the desired selection has been made.

Thanks to these tools, the installation describing the north/east wall and the mosaic floor of the *triclinium* has been constructed.

Results and conclusions

The use of new technologies applied to the communication and dissemination of cultural heritage has been popular for some years now. The small size of the archaeological site of *Domus Eleniana* and its protection against atmospheric agents, introduced when the Domus became a museum in 2007, allows us to make further steps ahead in research. In this environment, we could test a methodology consisting of a sensing activity through *3D laserscan* and *interaction design.* In this way, both visitors and scholars choose the type of information they are most interested in and the level of detailed exploration that they want to obtain. The 3D modelling of the *Domus* and the possibility to navigate it in real time, display it in *Augmented Reality*, or view its construction techniques thanks to *projection mapping*, constitute a comprehensive approach to communicate and disseminate any *Cultural Heritage*.

In the future, it will be important to verify whether this methodology can be applied to large outdoor archaeological areas, where some of the proposed solutions may not be negatively affected by the state of the places or by a possible lack of protection against atmospheric agents.

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Mieko Matsumoto and Espen Uleberg (eds) 2018. *CAA2016: Oceans of Data*
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
Oxford: Archaeopress

On Roof Construction and Wall Strength: Non-Linear Structural Integrity Analysis of the Early Bronze Age Helike Corridor House

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Abstract
This paper describes structural integrity analysis of the Early Helladic Helike Corridor House aimed at determining the nature of roof construction, and thus addressing two research questions: 1) Was the roof of a light tiled construction or was it heavier, similar to recent reconstructions of early Minoan dwellings; and 2) What would the behaviour of the structure be when subjected to adverse wet weather conditions under light and heavy roof loads. Using mechanical properties of dry and wet adobe bricks, simulations were performed under four conditions: LIGHT-DRY (light roof, dry adobe), LIGHT-WET, HEAVY-DRY and HEAVY-WET. Results show that under a light roof the structure would stand. However, under a heavy roof it would lead to total collapse of the house based on the Tensile Yield Stress on the wall structure. This points toward sophisticated construction techniques in a period where only scant evidence is available for tiled roofs, and the possible use of stabilising materials such as lime, ash or organics to protect and strengthen the tiles.

Keywords: Helike Corridor House, Early Bronze Age, Finite Element Analysis, Structural Integrity, adobe bricks

Introduction

Early Helladic Helike has been revealed as a major coastal and trade town centre of the second half of the 3rd millennium BC, on the south coast of the Gulf of Corinth, north–western Peloponnese, Greece. The geographic location of Helike is depicted in Figure 1. Helike was situated on the plain lying between the Selinous and Kerynites Rivers, south–east of the town of Aigion. The site has been buried for the last 4000 years due to dramatic subsidence caused by an earthquake followed by sediment deposition processes (Soter and Katsonopoulou, 2011). Its remains are presently lying buried between 3–5m under the coastal plain (Katsonopoulou, 2011). Stone foundation walls from the mainly rectangular buildings of various functions, interior floors, cobble paved streets, parts of a fortification wall, as well as multiple localized features from the interiors, including benches, floor-standing jars and cooking installations, compose an array of surviving remains from the lost town (Katsarou-Tzeveleki, 2011). The building plans provide a detailed view of town planning and the arrangement of public and private spaces of this Early Bronze Age urban centre, pointing to advanced local expertise, building and engineering skills and craftsmanship, possibly strengthened with significant technical input from the town's outward interaction.

The wall foundations consist of several layers of dry stones, unearthed to their full height in certain buildings. At least two eroded adobe bricks have been recovered from the settlement (Figure 2) with their size and shape giving an indication of construction techniques. The bricks' coarse texture can be related to the gritty quality of the storage and cooking containers found on the site. A large number of eroded light coloured clay lumps have also been recovered from the building. Although full laboratory analysis is underway, their particular texture and fabric, together with shapeless and eroded profiles would exclude them from being part of a vessel, and would instead strengthen their association with wall rendering materials.

The Helike Corridor House (HCH) is an advanced example of the extensively debated architectural template of the late EH II/early EH III (mid to second half of the 3rd millennium BC) on the Greek mainland (Shaw, 2007; Maran and Kostoula, 2014). The HCH has become the focus of analytical modelling and simulation

Figure 1. The geographic location of the town of Helike in the Peloponnese, Greece.

studies within the last couple of years (Kormann *et al.*, 2015). Although the detailed structure of the house was only excavated along its western section due to the rest of it extending into non-excavated neighbouring fields, its 'corridor' plan is evidenced by the arrangement of narrow corridors along the preserved external sides of an axial rectangular structure, composed of a series of adjoining rooms (Figure 2). The HCH was extended from an earlier ground-floor structure of a simpler rectangular plan at some point in the Early Helladic II/III, when the entire settlement underwent major architectural changes towards the adoption of clear town planning.

The rich excavated contents and the extent of the surviving part of the HCH have provided significant data enabling thorough approaches to the technical innovations of the period, offering strong evidence for the structural integrity of a two-storey, stairway-connected and multi-spatial complex building at Helike and beyond. In fact, the material and structural analysis of the particular HCH is expected to provide research with challenging implications that will go beyond the house's individual features, and will contribute to understanding the social and economic significance of the settlement itself and also the rise of the long-debated building type in the wider Early Bronze Age mainland context.

The remainder of this paper is organised as follows. The aims and objectives of the research are presented in Section 2 and the simulation methodology of nonlinear buckling analysis using ANSYS is presented in Section 3. Section 4 presents the results of the simulation studies and a discussion and conclusion is presented in Section 5.

Aims and oobjectives

The aims of the research are to provide a better understanding of building techniques in the context of the Helike Corridor House with particular reference to roof construction. The research focuses on roof loads by performing non-linear and sensitivity analyses addressing two research questions:

Figure 2. Upper: the Helike Corridor House stone foundations. Lower: sample of adobe brick H61.

1. Was the roof of a light tiled construction or was it heavy, similar to recent reconstructions of an early Minoan dwelling which are about four times heavier than a tiled roof?
2. What would the behaviour of the structure be when subjected to adverse wet weather under light and heavy roof loads?

Underlying these questions is the fact that in the Helike Corridor House excavations, evidence for roof or roofing materials has never been found. This research offers a new method of addressing the question of roof construction through modelling and simulation of the mechanical properties of the house structure under various roof hypotheses. Using Finite Element Analysis — FEA in connection with ANSYS it has already been established that the house plan modifications from an earlier design would be able to support a second floor (Kormann *et al*., 2015). Now it is proposed to establish the type of roof through modelling and simulation of different roof configurations under varying weather conditions. The following objectives are identified:

1. 3D modelling of a light tiled roof and of a heavy roof similar to Early Minoan construction, and determining their weights acting on the house structure when dry and when wet,
2. Using ANSYS, perform non-linear buckling FEA analysis under four roof configurations and weather conditions: light-dry, light-wet, heavy-dry and heavy-wet,
3. Analyse the results and draw conclusions related to the Helike Corridor House and the implications for other corridor houses and building techniques in the period.

Methodology

Finite Element Modelling with ANSYS

ANSYS (Lawrence, 2012; Sharpe, 2008) is an engineering modelling and simulation package for testing and validation of the physical behaviour of structures based on Finite Element Analysis and mechanical properties of materials. FEA is thus a computational method to analyse a material, object or structure, and determine how applied forces and stresses affect their physical behaviour. FEA is particularly useful for determining all weak points, normally before the object or structure is actually built. In the case of the Helike Corridor House, FEA is used to determine mechanical properties of the design, materials, structural strengths and weaknesses, and test several hypotheses or 'what if' scenarios.

FEA is only an approximation of the analytical solution, as many engineering problems contain a range of complex, non-homogeneous material properties and boundary conditions (e.g. localised applied forces and stresses), and the structure itself can be quite complex. The basis of FEA is to represent a body or structure into an assemblage of subdivisions called *finite elements*. The method translates partial differential equation problems into linear equations (Desai and Abel, 1972):

$$\{F\} = [K]\{q\} \quad (1)$$

where $\{F\}$ is the vector force acting on a node or finite element, $[K]$ is the stiffness matrix and $\{q\}$ is the nodal displacement vector. By applying the physical model to each node in the structure and then integrating (summing over) all nodes, the combined behaviour of the structure is obtained in terms of motions (displacements or deformations) and stresses which are used to predict whether the structure is prone to break or not. The integration using numerical methods involves two steps:

1. Divide the interval of integration (the more subdivisions the more precise are the calculations);
2. In each sub-interval, define simple physically-based functions to approximate the true functions. Some discontinuities such as cracks and inclusions in the bricks are very difficult to model, so the functions are only an approximation of the real ones.

The process is illustrated through the 3D model of the Helike Corridor House shown in Figure 3. The model is discretised by a meshing operation where each mesh element is a finite element. Nodes are the joining points between the mesh elements and, for each node, mathematical functions for the physical behaviour of forces and displacements are defined. As given by Equation (1), these linear functions with displacements at each node are the unknowns, and the system is solved for these using ANSYS. The results obtained are thus an approximation to the exact solution. The accuracy of the solution depends on the number of sub-intervals (how finely the mesh is sub-divided) and the chosen approximate mathematical function.

The general procedure to apply FEA with ANSYS to a model is described in 6 steps as follows. (1) Define the geometry of the model; (2) Assign material properties

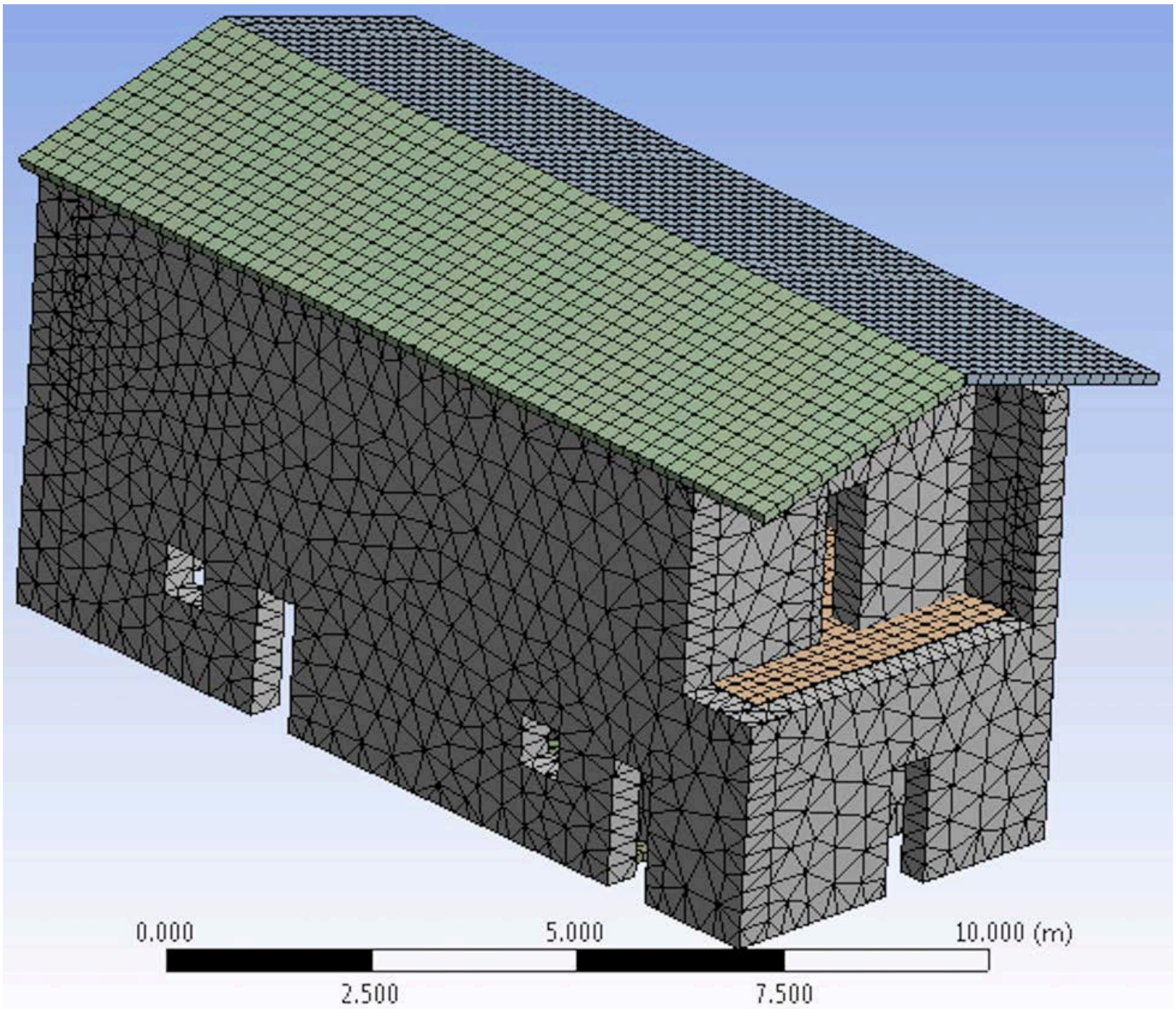

Figure 3. The Helike Corridor House. The FEA method requires meshing of the 3D model structure where each mesh element is a finite element.

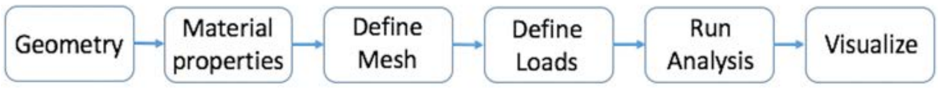

Figure 4. FEA methodology with ANSYS.

to its various parts; (3) Define a mesh operation on the model yielding its finite elements; (4) Define the loads, and inertial forces acting on the structure; (5) Select the analysis to be performed (e.g. static structural, linear buckling, non-linear, etc.) and run the model; and (6) Visualize and interpret the results.

The steps in the methodology, Figure 4, were applied to the HCH as follows. Normally, the geometry can be directly defined in ANSYS using one of the ANSYS packages such as Design Modeler or SpaceClaim. Alternatively, any CAD package can be used as 3D models and imported into ANSYS. Here the geometry of the Helike Corridor House has been defined using SketchUp (2015). The 3D model was exported to the intermediate IGS format (which is a standard 3D file format) and subsequently imported into ANSYS. The material properties of the HCH building materials namely adobe brick, *Pinus halepensis*, *Olea sp*, and reed *Arundo donax* are defined in the next Section. The meshing operation allows the user to control the accuracy of the simulation by applying fine mesh refinements. ANSYS provides a large choice of mesh elements, from solid to shell of various shapes and sizes to fit any complex geometry. Once the mesh is defined, the loads and displacements are applied to the structure followed by the selected analysis. Since the aims are to test the strength of the walls under various roof load conditions, the analyses comprise a linear Eigenvalue buckling analysis to determine the theoretical behaviour under applied loads followed by non-linear analysis. Finally, the results of the analyses are visualized and interpreted.

Linear and non-linear buckling analysis

Buckling analysis is normally performed to determine the critical loads where certain types of structures such as columns and tall walls become unstable. Each load has an associated buckling mode shape which depends on the geometry. There are two main ways to perform buckling analysis; namely Eigenvalue and Non-linear. Eigenvalue, also known as the classical Euler buckling analysis, computes the structural Eigenvalues for the given load constraints. It is a theoretical prediction that assumes all materials have ideal, perfect homogeneous properties (such as every single adobe brick being built to the exact same properties); normally real world structures do not possess the strength predicted by the analysis due to structural and material imperfections. For this reason, Eigenvalue buckling analysis is not recommended for the accurate predictions required in most real-world cases. Instead, it is used as a first step of a non-linear analysis by providing initial displacements at the onset of non-linear buckling.

Non-linear buckling is much more accurate and predicts buckling loads through non-linear large deflections and static analysis. This analysis requires small off-axis loads to initiate the desired buckling mode, and this is provided by the Eigenvalue buckling analysis. The mode of operation of non-linear analysis is to perform a gradual increase of the applied load or displacement according to Equation (1) until a load level is found in which the structure becomes unstable. This analysis allows the modelling or the accounting for geometric imperfections, material non-linearities, and other faults in the structure such as cracks or gaps.

Kormann *et al.* (2015) tested the strength of the Helike Corridor House design through linear buckling analysis using the load multiplier as a prediction of structural stability. The main goal was to determine whether or not the house design would be able to support a second floor, which was confirmed through simulations. In those simulations the buckling factor multiplier was used as a prediction and concluded that a more detailed non-linear buckling analysis was required, which is the subject of the analysis reported here. This paper extends that research to the non-linear case by varying the roof loads under varying weather conditions.

Figure 5 depicts the ANSYS pipeline for linear and non-linear buckling analyses. The deformations from Eigenvalue (linear) buckling obtained from steps A–B are fed into non-linear analysis where the buckling modes are used as large displacements (steps C–D–E). Once calculations are performed, it is necessary to verify whether or not the compressive and tensile strengths acting on the structure surpass the maximum allowed by the Compressive and Tensile Yield Strengths of the materials. If so, it may lead to rupture by unacceptably large deformations and possible collapse of the structure.

The mechanical properties of materials are described in Table 1. A crucial aspect of the research is to determine the mechanical properties of adobe brick when dry and under wet conditions (Brick H61 and Brick H61 Wet in Table 1). Normally, standardised destructive and non-destructive tests are carried out to determine

Material	Density, Kg.m^{-3}	Young's Modulus, MPa	Poisson's Ratio	Tensile Yield Strength, Pa	Compressive Yield Strength, Pa
Brick H61	1737	54.7	0.17	40,000	1.2E+06
Brick H61 Wet	1963	27.3	0.17	20,000	6E+05
Olea sp	990	17,770	0.25	3.1E+07	6.2E+07
Pinus halepensis	611	10,700	0.17	8.16E+07	6.1E+07
Arundo donax	234	9,000	0.25	3.21E+08	6.65E+08

Table 1. Mechanical properties of HCH building materials.

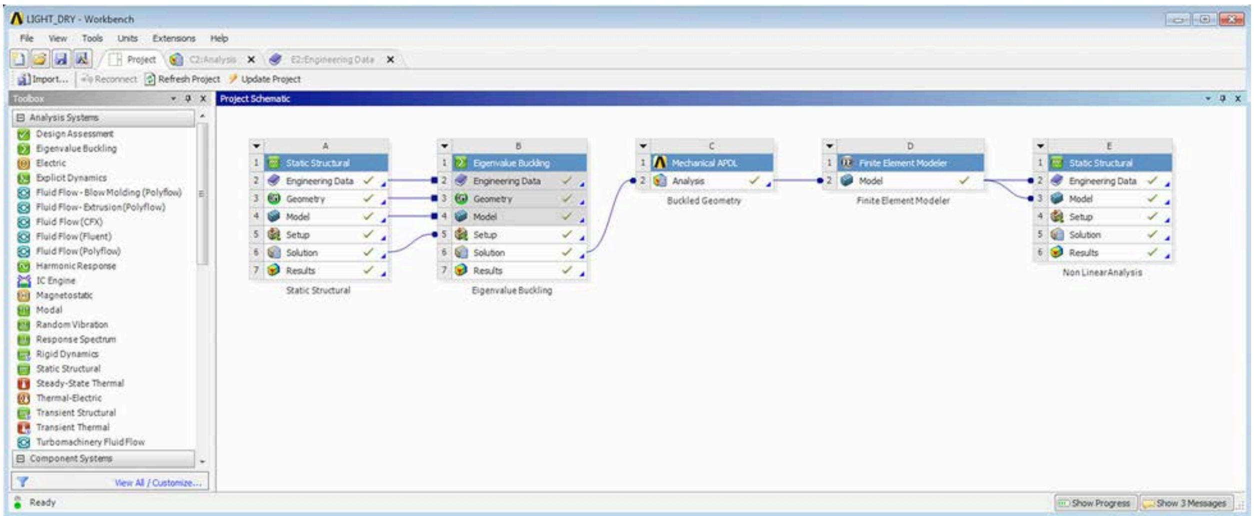

Figure 5. The ANSYS pipeline for non-linear buckling analysis.

mechanical properties of materials (Hibbeler, 2014). Since it is not possible to carry out destructive tests on the Helike samples, image-based analysis was performed yielding estimated composition of 30% gravel, 53% sand, silt and clay and 17% straw (Iliopoulos, 2014). The mean density of dry adobe brick was estimated at 1,737 kg.m^{-3} (Kormann *et al.*, 2015). The Young's modulus of elasticity (a measure of how elastic the material is) was assumed to be 54.7 MPa (Adorni *et al.*, 2013). The assumed Poisson ratio (a measure of elasticity expressed in percentage) was 0.17, the compressive strength 1.2 MPa, and the tensile strength 0.04 MPa based on Hejazi and Saradj (2014) and (Al-Jawadi, 2015). Note that Pascal (Pa) is a measure of pressure and Newton a measure of force (1 Pa=1 N.m^{-2}).

The mechanical properties of wet adobe bricks are taken from El-Mahllawy and Kandeel (2014) who determined that, on average, the water absorption by a spray method simulating rain was of the order of 13%, which is also confirmed by studies from Auroville Earth Institute (2015). Concerning compressive and tensile yield strengths, Njau and Park (2015) determined that the strength of an adobe block wall is decreased by 50% under water absorption tests, as confirmed by El-Mahllawy and Kandeel (2014).

The wooden components of the floor at the 'House of the Tiles' have been discussed by Maran and Kostoula (2014) as likely to have been built from transversal and longitudinal beams of the local species *Pinus halepensis*. *Pinus* is also assumed here for the construction of the wooden structures of the floor and roof of the Helike Corridor House. There is evidence for *Pinus halepensis* on the north—western coast of Peloponnese during the Holocene (Lazarova *et al.*, 2012), and in the Neolithic period, pine communities that dominated the landscape were strongly reduced during the Early Bronze Age, as confirmed by radiocarbon analysis of sediment cores (Lazarova *et al.*, 2012). The mechanical properties of *Pinus halepensis* quoted in Table 1 were determined by mechanical testing (Correal-Mòdol and Vilches Casals, 2012; Zanne *et al.*, 2009) and by similarity to related pine species (Ozkaya, 2013).

Results

Following the methodology defined in Section 3, we performed four simulation studies by varying the type of roof construction as exposed to both dry and wet weather conditions. According to Corridor House literature (Wiencke, 2000), a roof structure comprised three layers: a wooden frame, a layer of reeds and a

LIGHT ROOF		HEAVY ROOF	
Dry weight	Wet weight	Dry weight	Wet weight
234,081N (8,030Pa)	260,469N (8,935Pa)	859,902N (29,497Pa)	886,290N (30,402Pa)

Table 2. Weight of Light and Heavy roofs.

layer of mud/rammed earth or tiles. For the Helike Corridor House, we hypothesized and tested two types of roof construction; namely *Light* and *Heavy*. A *Light* roof comprised a supporting wooden structure of *Pinus halepensis*. The trellises were covered by a layer of reeds *Arundo donax* and a layer of clay and tiles. A *Heavy* roof was simulated similar to a recent Middle Minoan roof reconstruction (Beckmann, 2014; McEnroe, 2010) and comprises a heavy wooden structure, a layer of reeds, and a thick layer of mud. A heavy roof, as simulated here, would be over 3.7 times heavier than a light roof using the same proportions and materials as the above mentioned reconstructed Minoan roof.

In order to simulate rain and wet weather conditions, the roof and external walls were allowed to absorb 13% of water similar to the spray method reported by El-Mahllawy and Kandeel (2014). Consequently, the roof became heavier when wet, and the external walls experienced a corresponding decrease of 50% in the mechanical properties of Compressive and Tensile Yield Strengths (Njau and Park, 2015). The weight of the various roof configurations dry and wet are listed in Table 2, whilst the mechanical properties are listed in Table 1.

Four simulations were performed: LIGHT–DRY for light roof, dry conditions, LIGHT–WET, HEAVY–DRY and HEAVY–WET. The first step in simulation with ANSYS is to import the CAD model from SketchUp (Figure 6 top left). Since we are most interested in the behaviour of the walls by varying the roof load, the roof was removed and replaced by the equivalent weights as defined in Table 2. The weight is distributed evenly over the walls as shown in Figure 6 (top right painted red). Under the weight of the roof and gravity, the walls would deform linearly (ideal elastic deformation) downwards by around 6mm for the LIGHT–DRY roof as shown in Figure 6 bottom left. Linear Eigenvalue buckling analysis with two buckling modes is illustrated on the bottom right. These displacements are calculated for the four models light and heavy, dry and wet and then fed as initial conditions into non-linear buckling analysis.

Once linear Eigenvalue buckling is completed for all four cases, a non-linear analysis is performed. This procedure is known as static-nonlinear (defined in the E-box of Figure 5) in which the structure of the Helike Corridor House is subjected to the roof load in a monotonically increasing fashion, starting from a low value for the roof load and increasing in a specified number of steps until the final roof load is reached. This indicates at which load step the stresses acting on the structure may surpass the maximum allowed, if at all. The maximum allowed stresses indicate the range of elastic (desirable) performance; any value over these indicates inelastic behaviour and the structure may break or collapse.

In the simulations, as the weight of the roof gradually increases in steps until it reaches its actual weight, all forces and deformations are calculated for each step and recorded. This allows visualization of the forces, stresses and displacements at each simulation step and interpretation of the dynamic behaviour of the structure. For the Helike Corridor House, the most important parameter is the Tensile Yield Strength of the abode brick, as defined in Table 1 (the limits of Compressive Yield Strength are never reached in the simulations). As the forces acting on the walls increase at each step of the simulation the walls tend to buckle and, as they bend, the surface of bricks experience tensile forces which cause rupture if the maximum allowed is exceeded.

Figures 7–10 depict the deformations and stresses coloured by range of values. Figure 7 shows results for the LIGHT-DRY simulation. On the left, the total deformation from linear Eigenvalue buckling analysis; this is used as input to non-linear analysis and it is only shown here to visualize the buckling modes and which areas of the structure are subjected to larger deformations. On the right, the tensile stresses are indicated for each area of the structure. For the LIGHT-DRY the limit for tensile stress is 40,000 Pa for dry adobe. The simulation shows that walls are subjected to stresses of magnitudes up to 20,000 Pa indicated in the areas painted blue, light blue, and cyan. These results clearly indicate that the structure is stable under the applied LIGHT-DRY roof load.

Figure 8 shows results for the LIGHT-WET simulation. On the left is depicted the linear Eigenvalue buckling deformation and on the right the stress map is shown. The stresses on the walls are indicated in blue, light blue and cyan with magnitudes up to 11,487 Pa. This is less than the maximum allowed of 20,000 Pa for wet adobe, indicating that the structure is stable under the roof load. Note that stresses on wet adobe are less than stresses observed on dry adobe of Figure 7 for the same

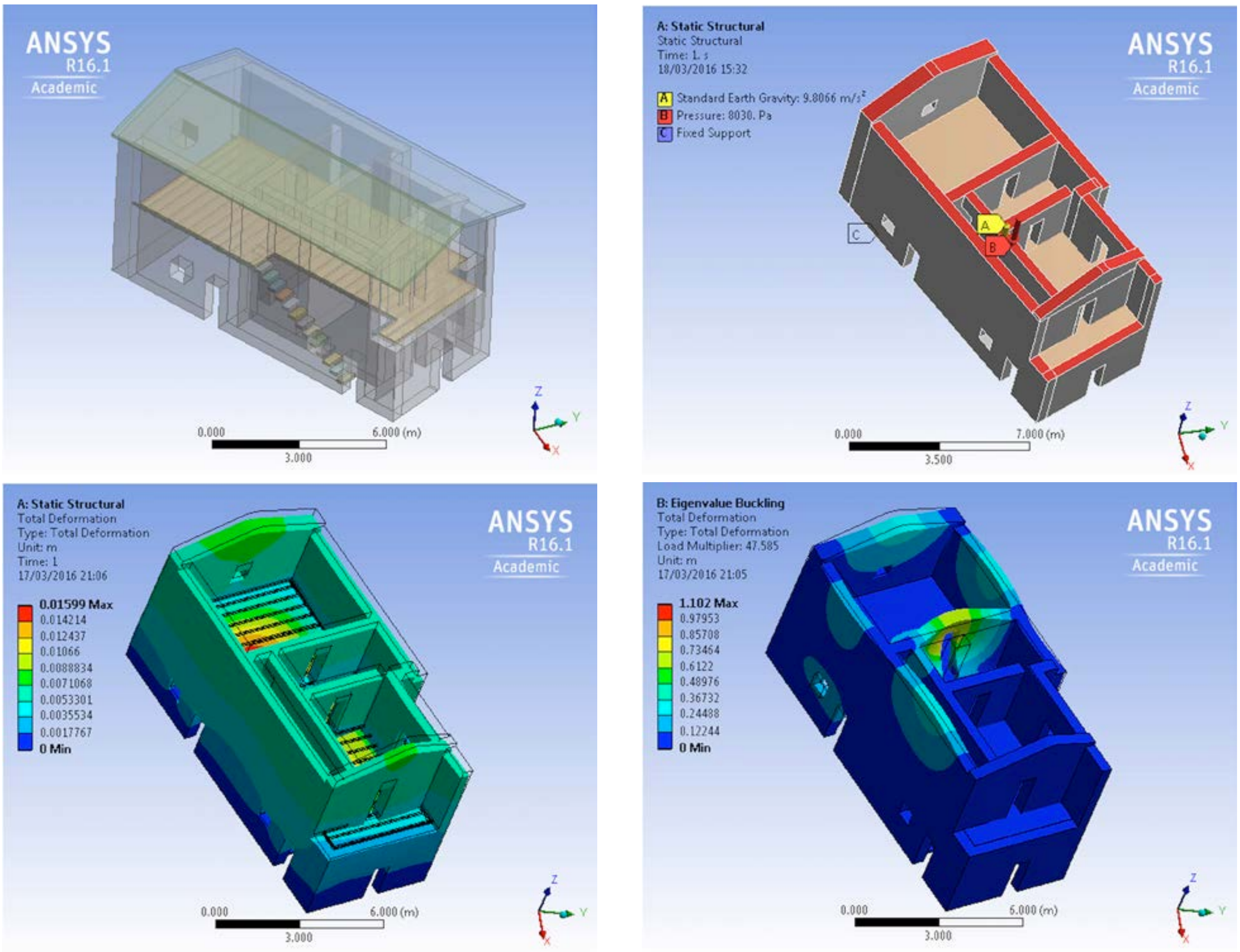

Figure 6. Top left: the imported Helike Corridor House from SketchUp; Top right: the roof was removed and replaced by its weight acting on the structure (LIGHT-DRY case is illustrated here). Bottom left: linear elastic deformation; Bottom right: linear Eigenvalue buckling.

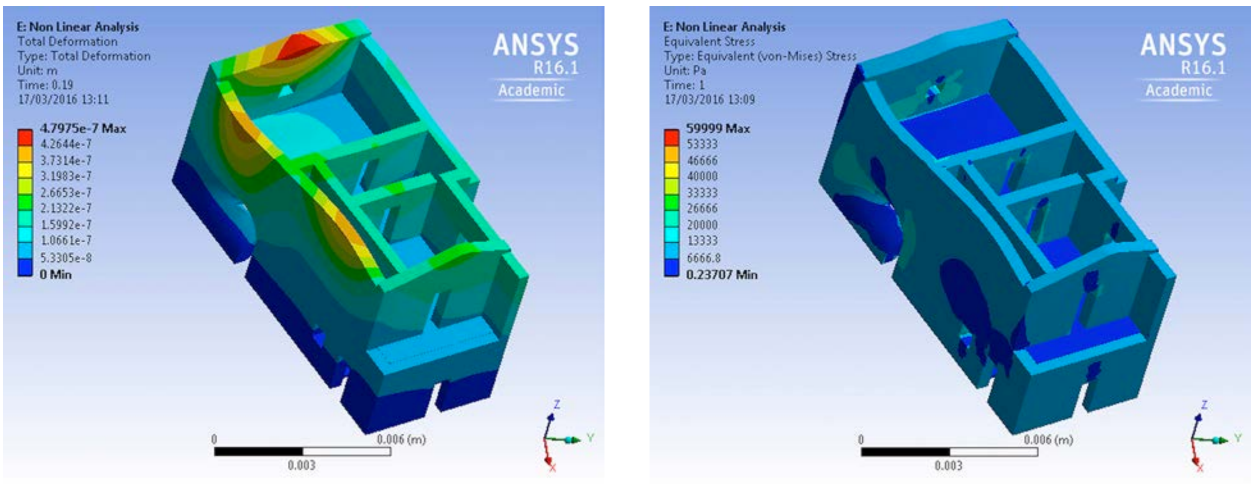

Figure 7. Non-linear analysis for LIGHT-DRY model. Left: total deformation, right: stress analysis.

roof load. This is expected, as wet adobe becomes more elastic than dry and thus, the experienced magnitudes of tensile stresses are lower. While the tensile yield strength of wet adobe is 50% of that of dry adobe the structure, however, remains stable for the LIGHT-WET case.

Figure 9 depicts results for the HEAVY-DRY simulation. On the left, the two-mode Eigenvector buckling analysis deformation is shown. The stress map is depicted on the right. The figure legend shows that the turquoise band corresponds to stresses between 35,579–47,439 Pa, indicating failure of the structure as the maximum of 40,000 Pa for dry adobe is exceeded. Anything above that (green, light green, and yellow as observed in the model) would equally indicate structural failure. The model of the Helike Corridor House shows large areas of turquoise, green, light green and yellow indicating therefore, that the structure would collapse under the HEAVY-DRY roof load.

Figure 10 depicts on the left the deformation from Eigenvalue buckling analysis for the HEAVY-WET model. On the right the stress map is depicted. The areas painted light blue correspond to stresses of 15,372–30,744 Pa exceeding the maximum of 20,000 Pa for wet adobe. Other bands yield stresses even higher indicating that all walls would collapse under the HEAVY-WET roof load.

Discussion and conclusions

This paper has investigated possible scenarios concerning roof construction of the Helike Corridor House. Since no evidence of roof structures has been found at the excavated site, the aims of the research

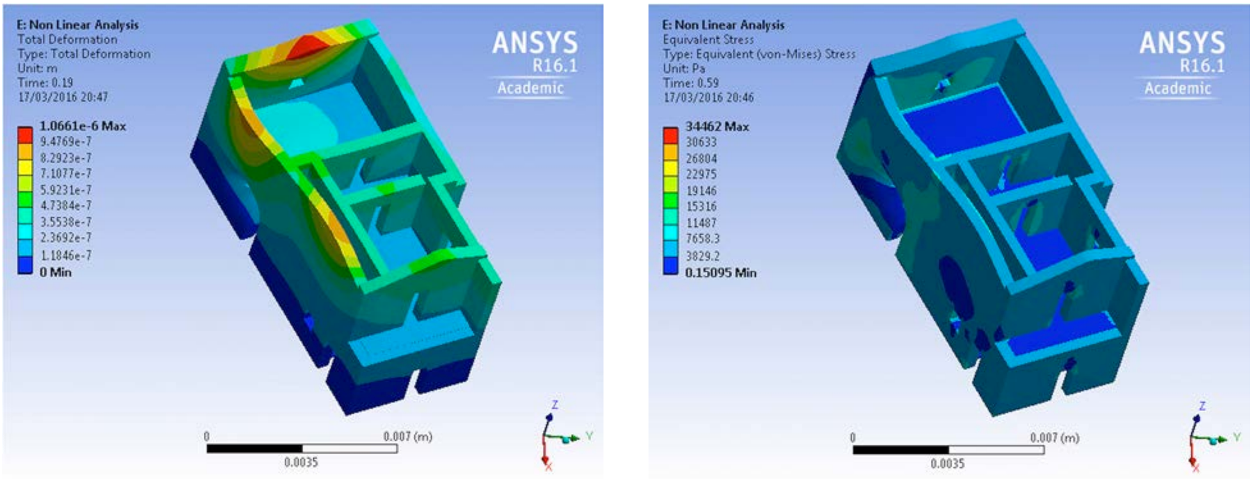

Figure 8. Non-linear analysis for LIGHT-WET model. Left: total deformation, right: stress analysis.

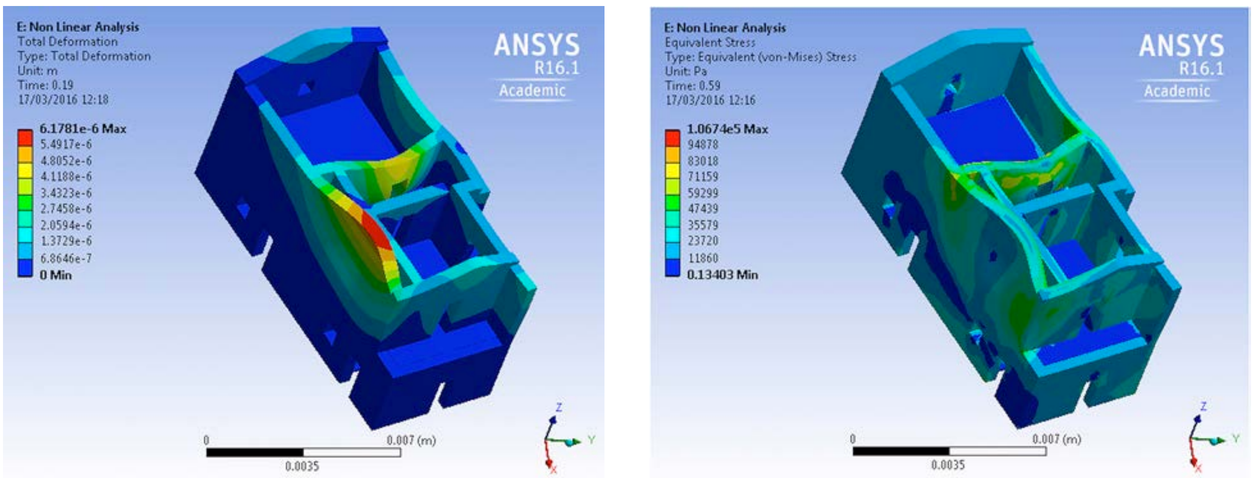

Figure 9. Non-linear analysis for HEAVY-DRY model. Left: total deformation, right: stress analysis.

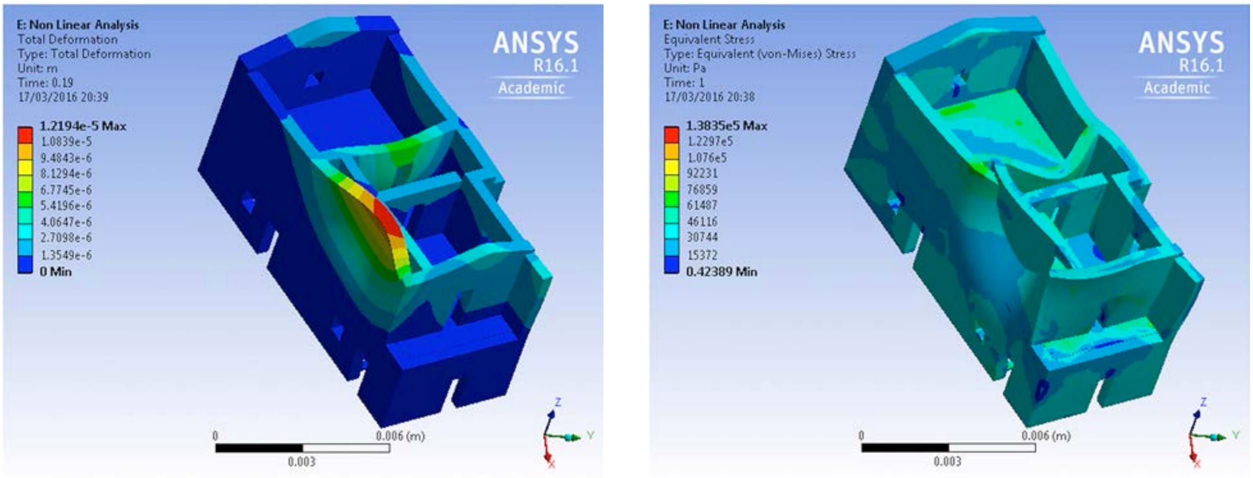

Figure 10. Non-linear analysis for HEAVY-WET model. Left: total deformation, right: stress analysis.

were to get a better understanding of roof materials and structure through modelling and simulation studies. The site has been buried under the water table for the past 4000 years, and unfired materials have not survived. Two types of roof were simulated, namely light and heavy under two weather conditions of dry and wet. The mechanical properties of the Helike Corridor House materials were defined with special focus on dry and wet adobe bricks as the simulations were focused on the wall strengths under the various roof configurations.

Results clearly indicate that if the roof were of a light construction with a wooden structure, a layer of reeds, and a layer of clay covered by tiles, the house walls would be able to easily stand the weight and stresses. This is for both cases of dry adobe and under adverse weather conditions with maximum water absorption of 13%. Note that under wet conditions, the roof becomes heavier and, at the same time, the walls are weakened by 50% concerning their Compressing and Tensile Yield strengths. The models show that under these conditions, wet walls would be able to support the roof load.

Results also clearly show the weakness of the structure under a roof of heavy construction with a wooden structure, a layer of reeds, and a thick layer of mud. Under such a load of about 3.7 times heavier than a light roof, the stresses on the walls would be larger than the Tensile Yield Stress maximum allowed threshold of 40,000 Pa for dry and 20,000 Pa for wet adobe brick. This means that the house would have collapsed under such a heavy roof, and thus it is unlikely that Minoan roof techniques were used.

The conclusion drawn from the simulations is that the Helike Corridor House roof was of a light construction covered by tiles. Evidence of tiled roof can be found in only a few corridor houses such as 'The House of the Tiles' at Lerna, at Tiryns and in the Argolid region (Shaw, 1987). The majority of corridor houses show no evidence for tiled roofs and, in the absence of archaeological evidence, the assumption of a tiled roof can be generalised to other corridor houses of the period from the results shown here.

This analysis has made two significant contributions. First, it provides a better understanding of roof techniques and weight limitations for adobe built Corridor Houses in a period where only scant evidence is available. It is shown that the Helike Corridor House roof structure was most likely covered by tiles, and the results point to sophisticated construction techniques with tiled roofs and the possible use of stabilising materials such as lime, ash or organics to protect and strengthen the tiles. The theory that Helike builders were aware of such techniques can only be supported by the forthcoming detailed soil analysis to identify possible stabilisers, and this would raise further questions on wider interactions, such as trade. Helike is known to be an important trade centre in the EH II/III period and has the most significant corridor houses in Greece in terms of vessels and artefacts found, as no other EH corridor house site has provided such an array of vessels.

Second, the methodological approach to modelling and testing the structural integrity of the Helike Corridor House using finite element analysis with ANSYS has allowed the determination of the weak points in the structure. Non-linear modelling through buckling analysis has clearly shown whether the structure was able to support a heavy load or not, and this method could be extended to all archaeological structures where structural integrity is of interest. Furthermore, hypotheses can be built and tested concerning a wide range of 'what if' scenarios, provided that the geometry of the structures and the mechanical properties of materials are known.

Future work will be focused on finding evidence for tile materials through forthcoming full laboratory analysis of soil samples associated with the foundation walls. The method will also be applied to simulate the behaviour of the house structure exposed to an earthquake and determine the minimum earthquake intensity required to destroy the house and the implications of such results to the observed abandonment of such construction techniques in the Early Helladic period.

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Mieko Matsumoto and Espen Uleberg (eds) 2018. ***CAA2016: Oceans of Data***
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
Oxford: Archaeopress

An Exploratory Use of 3D for Investigating a Prehistoric Stratigraphic Sequence

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Abstract

One of the purposes of a research recently started at Lund University was to test the use of 3D technology as an exploratory tool for data analysis. The combination of advanced 3D acquiring techniques and GIS software capable of dealing with geometrically complex 3D information has been tested to investigate one of the most outstanding archaeological sites in Scandinavia, the prehistoric cave of Stora Förvar in Stora Karlsö, Gotland (Sweden). In particular, the main objective of this paper is to show the possibility of reusing information provided by the original field reports from 1940s and to combine it with a 3D model of the cave in order to digitally reconstruct the stratigraphic sequence as it was documented by excavators. Such a reconstruction will be the basis for performing 3D spatial analysis over the sequence and to spatially investigate artefacts distribution.

Keywords: 3D GIS, spatial analysis, archaeological stratigraphy, prehistoric cave, Mesolithic archaeology

Introduction

Investigating a prehistoric cave through the combined use of digital methods can provide archaeologists with innovative solutions that might be decisive in the final process of data analysis and interpretation. The present paper aims at discussing an innovative work pipeline to reuse old archive material, in the form of hand-made drawings and handwritten artefacts tables. The idea is to combine this material with a digitally-acquired 3D model of the cave in order to produce a virtual replica of the stratigraphic sequence and its related artefacts, as it was documented by archaeologists who conducted the excavation in the end of the 19th century. Such a data integration is the essential premise to further our current knowledge about the original spatial location of more than 7000 artefacts collected at the time of the excavation. Having a quantitative assessment of their distribution throughout the sequence of arbitrary layers as they were documented, would allow us to infer patterns of presence, and possibly to generate new insights into the different habitation phases of the cave. The study area is located in South–Eastern Sweden, on the small island of *Stora Karlsö,* and the investigated site is the prehistoric cave of *Stora Förvar* (Figure 1). It being a part of an ongoing research project, the main objective of this paper is to present the preliminary results of data implementation, which allowed us to use the old archive material in combination with the 3D models of the cave, in order to reconstruct the original stratigraphic sequence composed of 30 cm thick arbitrary layers by which it was excavated. Such a reconstruction has been achieved by combining laser scanning-derived data and ESRI ArcGIS 10.3 software, which is currently one of the few GIS platforms enabling users to import and manage geometrically-complex 3D boundary models.

Research context

The renewed investigation of the *Stora Förvar* cave sequence is an important part of the research project 'The pioneer settlements of Gotland' (funded by the Berit Wallenberg Foundation, Swedish Research Council and Palmska stiftelsen). Amongst the handful of known Mesolithic sites from Gotland, the cave sequence of *Stora Förvar* is the most important one. It was excavated between 1888 and 1893, and produced a huge amount of archaeological material (Schnittger and Rydh, 1940). While the finds material was, for a long time, considered to be mainly Neolithic, a series of AMS-dates published in the 1990s revealed that the lowest levels of the cave were dated to the Middle Mesolithic period (7200–6000 cal BC) (Lindqvist and Possnert, 1999). The find materials in these layers consisted of huge amounts of human remains, faunal remains (mainly seal but also fish, hare and bird bones), stone axes, simple bone tools, cores, flakes and blades from a variety of raw materials, but mainly of erratic, local Ordovician flint.

The original sequence was excavated in several different sections, most of them stretching from one cave

Figure 1. The cave of Stora Förvar is located on the small isle of Stora Karlsö, west of Gotland, in South–Eastern Sweden (data source: ESRI ArcGIS online).

wall to the other, and in mechanical spits of c. 30 cm (equalling one Swedish Foot). This choice of excavation method was fairly modern for its time but has proven to be problematic since it did not consider the actual layers that can be seen on the original photographs of the profiles. Therefore any evaluation of the actual stratigraphy of the cave has to be based on statistics from the distribution of the mass materials, such as pottery, flint and faunal remains. Such evaluations have been published (see for instance, Pira, 1926; Clark, 1976; Ericsson and Knape, 1990; Lindqvist and Possnert, 1999; Apel and Storå, 2016) but since the cave walls are uneven, it has always been difficult to estimate the true volume in each spit, and therefore to understand the significance of the distribution of mass materials in the cave — something that is of vital importance for the project.

In 2013 we conducted a small research excavation of the cave floor (Apel and Storå, 2015) in order to see if we could detect untouched pockets of cultural layers in the cave floor. In connection with this excavation, the cave was subjected to a complete scan and a digital three-dimensional model was created. Additionally, in the framework of this project, we started to reconstruct the sections and spits of the original excavation from the old excavation reports and a preliminary analysis —aimed at defining the Mesolithic component of the cave sequence — which has been made in the form of a Master thesis (Lundström, 2016).

Methodological framework

Theoretical background

In recent years, the advances that have occurred in the field of archaeological computing allowed archaeologists to significantly benefit from the application of integrated techniques for the visualization and analysis of archaeological evidence (Dellepiane *et al,*. 2012; De Reu *et al*., 2013; Dell'Unto *et al*., 2014). In particular, new methods of 3D acquisition and reconstruction enormously impacted on the strategies of site documentation (Katsianis *et al*., 2008; Callieri *et al*., 2011; Opitz and Nowlin, 2012; Campana, 2014; De Reu *et al*., 2014), leading to an increase of reflexivity in the practice of archaeological excavation (Hodder, 2000) and opening new questions about the role of three-dimensionality in archaeology (Forte *et al*., 2012: Berggren *et al*., 2015). In this respect, one of the key points emerging from one of the latest CAA meetings was the lack of a real discussion about the analytic use of 3D in archaeology, as most of the articles produced in recent years have been mainly focusing upon visualization-related issues. As pointed out by some authors (Gillings and Goodrick, 1996; Frischer, 2008), a more thorough consideration of the 'heuristic' potential connected to 3D technology would help archaeologists to take advantage of three-dimensionality as an additional component of data analysis. An important contribution in this sense has been recently provided by the use of state-of-the-art 3D GIS platforms, where the combination of geometrically-accurate 3D models and advanced spatial analysis tools opened new scenarios of data visualization and analysis (Dell'Unto *et al*., 2015). In particular, the combination of 3D model's geometric high accuracy, resulting in a more 'objective' representation of the reality to be investigated and the analytic tools commonly available in GIS, let archaeologists experiment with innovative ways of using three-dimensionality to investigate spatial relations in the field (Wilhelmson and Dell'Unto, 2015), for example to detect visual patterns in an ancient built environment (Landeschi *et al*., 2016) and to make an assessment of the degree of degradation associated to ancient walls (Campanaro *et al*., 2015). In addition, the possibility to import and manage polygon meshes at different density values allow users to operate in a multi-scalar perspective, spanning from the single artefact to the wider landscape. Although this is not a per se new issue in GIS, the innovative aspect is given by the possibility to operate at different scales of resolution directly on the 3D models imported in the georeferenced space, improving the data accuracy and subsequently, the reliability of the interpretation.

These advances are particularly remarkable in the study of prehistoric caves, where the virtual reconstruction of the physical space is quite difficult, due to the complexity of the acquisition pipeline and to the irregularity of the geometry. So far, very few studies have included the use of 3D and GIS for investigating a prehistoric cave, and none of them have presented a real integration between the two methods. As an example, it is worth mentioning research conducted in a Palaeolithic cave in Spain, where a combined use of 3D acquisition techniques such as Terrestrial Laser Scanning (TLS) and close-range photogrammetry allowed archaeologists to improve the overall degree of data accuracy in the documentation process compared to traditional, bi-dimensional acquiring techniques (Lerma *et al*., 2010). A similar approach but with the specific purpose of documenting rock art was adopted in the Neolithic cave of *Grotta dei Cervi*, in Italy, where a multi-resolution laser scanner was employed in combination with a digital camera for the reconstruction of a textured model, to be used for a very detailed analysis of pictographs observed in the cave (Beraldin *et al*., 2006). On the other hand, the introduction of GIS-based tools in the analysis of cave environments distribution provided archaeologists with the opportunity to formalise, through a quantitative approach, the investigation methods and to use statistics for better understanding relations between artefacts, human remains and their original contexts, taking into account the spatial component of the objects retrieved in the field (Herrmann, 2002; Moyes, 2002). Still, in one example, the main limitation of a comparable approach was due to the bi-dimensionality of the data representation; that actually prevented a full understanding of the physical relations among the objects being excavated. The bi-dimensionality made it impossible to take advantage of the z axis as an additional factor for studying the artefacts distribution and problems related to, for example, their vertical movement through the deposits (Hiscock, 1985).

A recent attempt to combine stratigraphic information with a 3D reconstruction of a cave was done under the framework of a research project recently developed in Eastern Spain, in the *Pastora* cave (García Puchol *et al*., 2013). Here, the idea was to retrieve old site documentation in order to reconstruct the cultural layers in which part of the funerary material dated between the Neolithic and the Bronze Age was collected. The main problem in this case was the lack of a clear method of excavation (it was conducted during the 1940s by an amateur archaeologist) which prevented archaeologists from detecting precise stratigraphic units, as they were basically defined by the original plans on which the artefacts were laying at the time of the excavation. Still, the project showed how effective a 3D visualization of the artefacts represented in their original context could be, especially for the purpose of highlighting their reciprocal position in the space of the cave. This facilitated, as an example, the general understanding of the cave-related problems to visitors from the general public in the context of a museum exhibition. In brief, if it is the case that in the last few years there has been a general acknowledgement of the importance of using digital methods as a way to improve documentation strategies, there is still a lot of work to be done in order to effectively use three-dimensionality as an additional factor in support of—not just data visualization—but also for the analysis of archaeological evidence and its original context. As this paper seeks to demonstrate, the integration of 3D technology and GIS platforms could provide significant advantages in the study of prehistoric caves and their related material, enhancing the possibility for archaeologists to investigate relations and interactions among the objects along the full space of x, y, z Cartesian coordinates.

Acquiring the cave

The 3D-acquisition of the cave of *Stora Förvar* was done during two days in the summer of 2012. The instrument used was a Faro Focus 120S phase shift variation 3D-scanner (Figure 2). It was decided early on that since the main goal of the project only needed a geometrically correct 3D-model of the cave, there was no need to capture the colours.

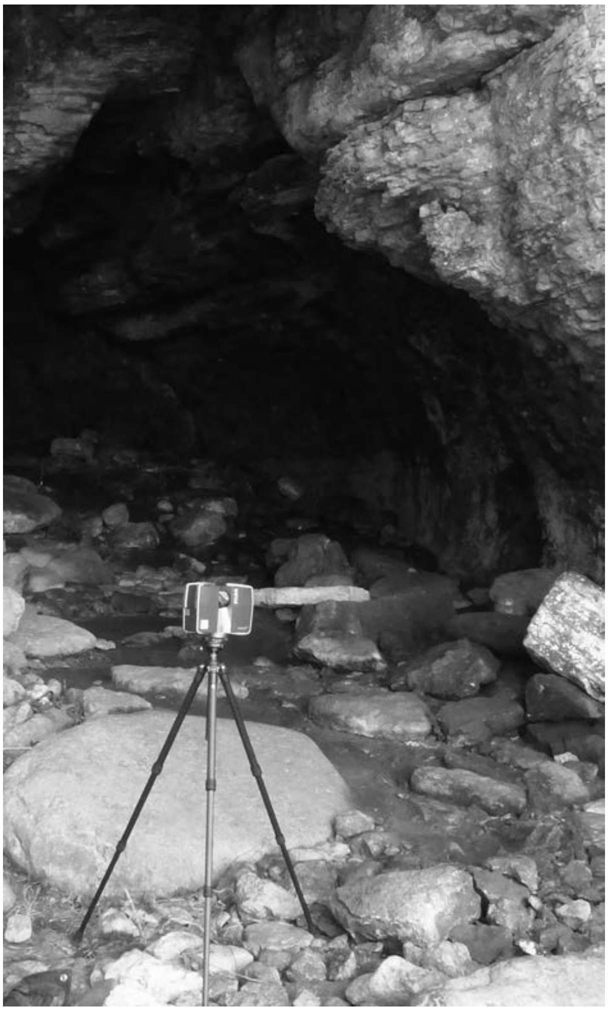

Figure 2. Faro Focus 120S phase shift variation 3D-scanner placed at the cave entrance.

Each scanning results in a points cloud containing millions of points (in this specific case 12 million points per scan) and in each scan the position of the scanner is automatically set as the centre of its own local coordinate system. The first step in the post processing is to place each scan in the correct position in a common coordinate system. This process is known as registration or alignment of the scans. Therefore it is important to choose a suitable strategy for the acquisition campaign in order to facilitate the registration. There are several different methods that can be used, for example measuring each scan position with a total station or differential GPS, or place different markers in the volume that is to be scanned. But considering the instruments available, the short timeframe in which the recording had to be done and the complex geometry of the ceiling of the cave, the method used was to record a relatively large number of scans to get a good overlap between scans. This method is the fastest acquisition method, but it requires more time during post processing since the registration has to be done manually. The scans were recorded at 30 different positions, which is quite a lot for such a small volume. But this method gave a good overlap between the scans and, more importantly, it created a good model of the complicated geometry of the ceiling. Finally some easily recognised features were marked out to be measured with a total station later on, making it possible to correctly place the cave in a GIS platform.

Reconstructing the sequence

The process of 3D reconstruction of the stratigraphic sequence as it was documented back in the 1940s (Schnittger and Rydh, 1940) has been based on the integration of different types of sources, spanning from archive documents to laser scanning data. Additionally, more information derived from the Swedish National Land Survey agency (Lantmäteriet, 2015) was considered as an important element to be used to better contextualise the original sequence in the wider context of the landscape of *Stora Karlsö*. The

ESRI ArcGIS 10.3 software package was chosen as a platform to develop this analytical workflow, it being the best-fitting operational framework for a number of reasons. First of all, recent advances have occurred in the 3D Analyst module (ESRI, 2015), allowing users to implement geometrically-complex three-dimensional boundary models, known as multipatch feature classes (ESRI, 2012) in a georeferenced environment (Optiz and Nowlin, 2012), where analytical tools can be used in support of data analysis (Landeschi *et al*., 2016). Secondly, an advanced 3D editing tool can be employed to draw and add new features as vector three-dimensional primitives (points, lines, polygons), that can be used to better describe multipatch geometries, improving the quality of data interpretation (Dell'Unto *et al*., 2015; Landeschi *et al*., 2015). Then, a geodatabase structure, which is now a de facto standard in the management of archaeological projects (Tennant, 2007; Katzianis *et al*., 2008; Nekhrizov *et al*., 2012; Müllerová *et al*., 2013; Van Ruymbeke *et al*., 2015) has been designed with the purpose of collecting and managing a heterogeneous quantity of data derived from different sources. The particular data format available in ESRI ArcGIS (ESRI, 2016) allowed us to customise the data management system so as to tailor it to the needs of the research

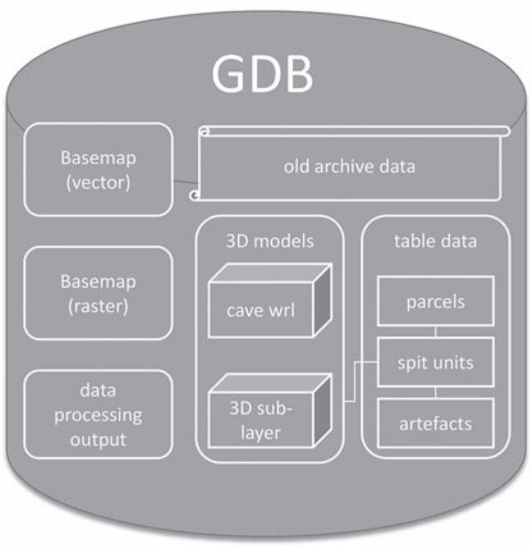

Figure 3. Relational geodatabase (GDB) containing all of the different data sets employed in the process of implementation and analysis. Basemap information was derived from the Swedish National Land Survey agency (Lantmäteriet) and has been organised in vector and raster file formats. Old archive data and a wrl model of the cave have been combined together in order to define the boundaries of the original arbitrary layers (spit units) documented by archaeologists in the 1940s. The obtained three-dimensional sequence was then connected to the tables related to archive information (unit names, parcels, artefacts).

project, providing final users with an effective and easy-to-use tool for data retrieval and analysis. In this respect, data have been reorganised in raster, vector and table data and divided based on their informative function. Firstly, a feature data set was specifically implemented to gather all the information derived from the Swedish National Land Survey agency so as to provide a general spatial context to the site of *Stora Förvar*. A further feature data set has been created to contain all the 3D objects connected to the cave representation, in the form of multipatch feature classes. An additional feature data set was then added to collect all the shapefiles created in the process of data analysis, and finally, more data sets were generated at a later stage to collect all the operational layers originated, as described later on, from the 3D sequence setup process (Figure 3).

Another category of data was represented by archival materials, namely all of those data derived from the 20th century field documentation that was produced and published approximately fifty years after the completion of the excavation. Such material was an essential element for this project as it provided in a graphic format information about the cave sequence as it was observed by archaeologists in the field at the time of the excavation. In particular, one of these hand-made drawings represented the original profile and the stratigraphic sequence. This was essentially an accurate representation of the vertical parcels and horizontal units on the site, which the excavation sequence divided, as a part of the excavation strategy based on the arbitrary layers method (also known as 'spit unit' method) (Hughes and Lampert, 1977). The units or arbitrary layers consisted of soil units excavated with a predefined depth of 30 cm. The 3D reconstruction of the cave sequence was basically the result of the combined information resulting from this profile drawing, one more plan drawing and the model derived from the laser scanning of the cave (Figures 4 and 5).

Data implementation

As a first step in the data implementation, the 3D model derived from the laser scanner acquisition had to be optimised in order to be correctly visualized in the Arcscene viewer. For this purpose, the original 10 million-faces mesh was decimated down to 1 million in MeshLab (MeshLab, 2016) and then converted into a VRML file; one of the file formats currently accepted by ArcGIS (ESRI, 2014). The function of 3D data import was used to visualize the object as a multipatch feature class in a randomly assigned portion of the scene, as no previous spatial information were given to the geometry, it was instead identified by local coordinates. To address this issue, some reference points were added as a point shapefile to the project; those which

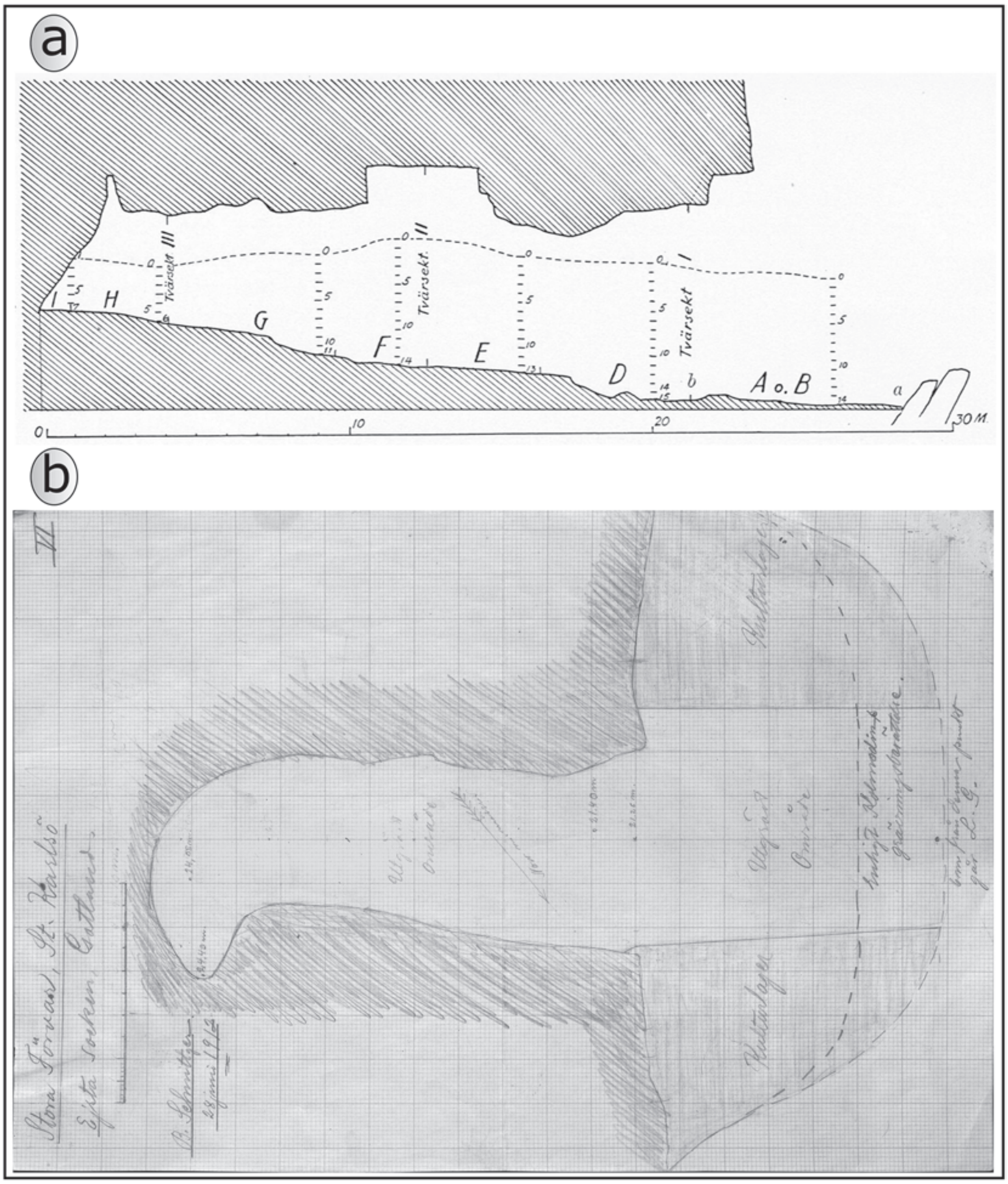

Figure 4. Original hand-written drawings used as a spatial reference for the stratigraphic sequence reconstruction (after Schnittger and Rydh, 1940): (a) the profile of the cave, illustrating all the different parcels (named from letter A to I) along with an accurate account of the 30 cm-thick arbitrary layers generated by excavation, starting from layer '0' and numbered with progressive values down to the cave floor. (b) The plan drawing has been employed to define the boundaries of the stratigraphic sequence just outside the entrance of the cave, where the absence of cave walls prevented us from clearly define the limits of the excavated deposits.

were previously acquired in the course of a total station survey carried out in the field in October 2014. Then the multipatch of the cave was edited and moved along x, y, z axes in order to exactly match the reference shapefile, and be in the right geospatial location (Figure 6).

At this stage of the process, the 3D model of the cave was imported without any texture, as the main goal was to have the geometrical boundaries of the cave in GIS, to be used as a reference for reconstructing the stratigraphic sequence. Adding a texture, other than being a useless effort due to the absence of any relevant information to be used in this project, would have made the overall process of data visualization and management more time-consuming. At a further stage of data implementation, the profile drawing of the cave was imported and put in relation to the previously described 3D model of the cave. To do that, the original printed version of the drawing was digitally acquired and then imported as a texture image draped on a

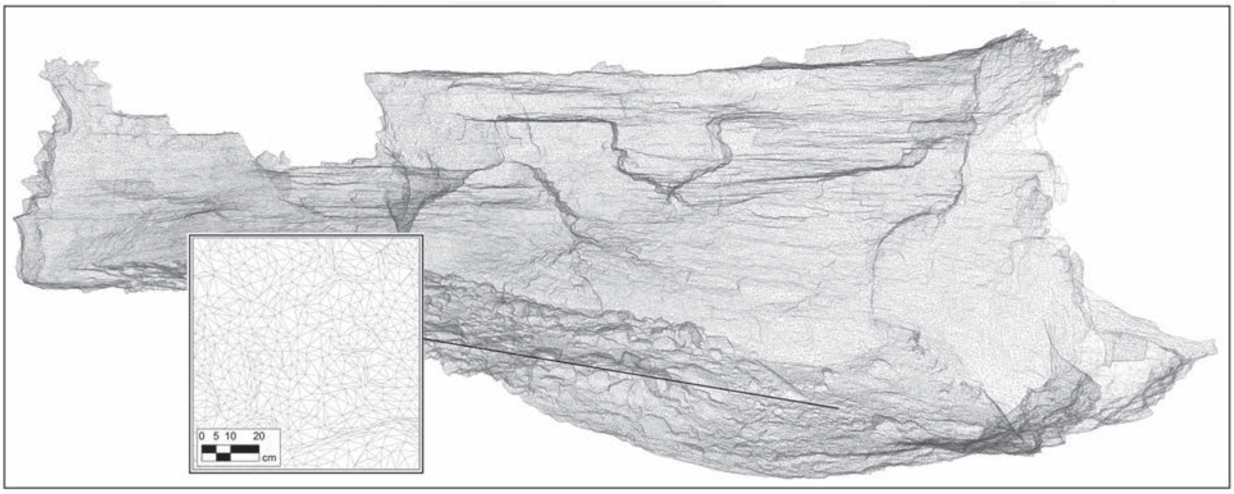

Figure 5. 3D model of the cave as a result of the laser scanning acquisition and the mesh decimation operated in Meshlab: from the original 10 million-points models, mesh density was reduced to 1 million in order to be properly imported and managed in ArcScene.

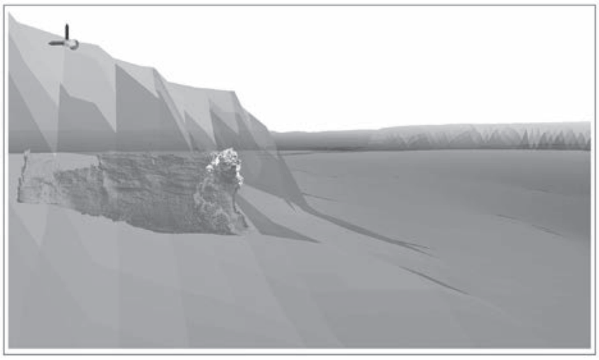

Figure 6. Cave model has been converted into a COLLADA file and imported in the previously designed GDB as a multipatch feature class. The georeferencing allowed us to relate it to different thematic layers connected to the surrounding landscape, such as the Digital Elevation Model (DEM) of Stora Karlsö (data source: Lantmäteriet).

3D rectangle COLLADA file, which was rescaled to the actual size indicated by the drawing itself, so as to exactly re-project the position of each single arbitrary layer in the three-dimensional space and in the right spatial relation to the cave. In particular, the most relevant information that was conveyed by the hand-made profile drawing was related to the z value and the length along the main axis of the cave of each single arbitrary unit. Combining these data with the geometry of the cave's boundaries allowed a clear definition of the x, y, z values for all of the units identified in the cave stratigraphy. At a later stage, specific shapefiles were created in order to vectorise information derived from the profile drawing in the GDB. In particular, in accordance to the documented sequence partition, the original excavation area was divided into six different parcels, starting from the cave entrance to the innermost part and then marked with letters (from A to I). A point shapefile was hence used to mark the intersection between each parcel's boundary and the single arbitrary units; subsequently a polyline shapefile was created to connect all of these points and generate each layer's upper and lower interface (Figure 7).

Then, every single interface line was turned into a horizontal plan, which was assigned with a sufficiently large value of width in order to make it intersect the boundary of the cave. Such intersection allowed for the creation of a polyline shapefile representing the external boundaries of each arbitrary layer previously originated from the interface line. Essentially, each arbitrary layer was defined by a couple of external polylines that constituted its boundaries along the cave wall. These polylines were then closed in order to be turned into a polygon shapefile that was exactly describing the area of each unit's interface (Figure 8).

At this stage of the process, the idea was to extrude each arbitrary layer polygon 30 cm along the z axis in order to obtain the volumetric information. After some attempts, we soon realised there was an error due to an oversimplification of the actual volumetric space of each layer. Such an error was due to the fact that each polygon was automatically extruded 30 cm all the way along its perimeter, without taking into account of the irregularity of the cave walls which actually 'cut' the extruded polygon, leaving some portions of the volume protruding outside the boundary of the cave or, on the opposite, leaving some empty space inside the cave boundary, depending on the slope orientation of the cave wall (convex vs. concave) (Figure 9).

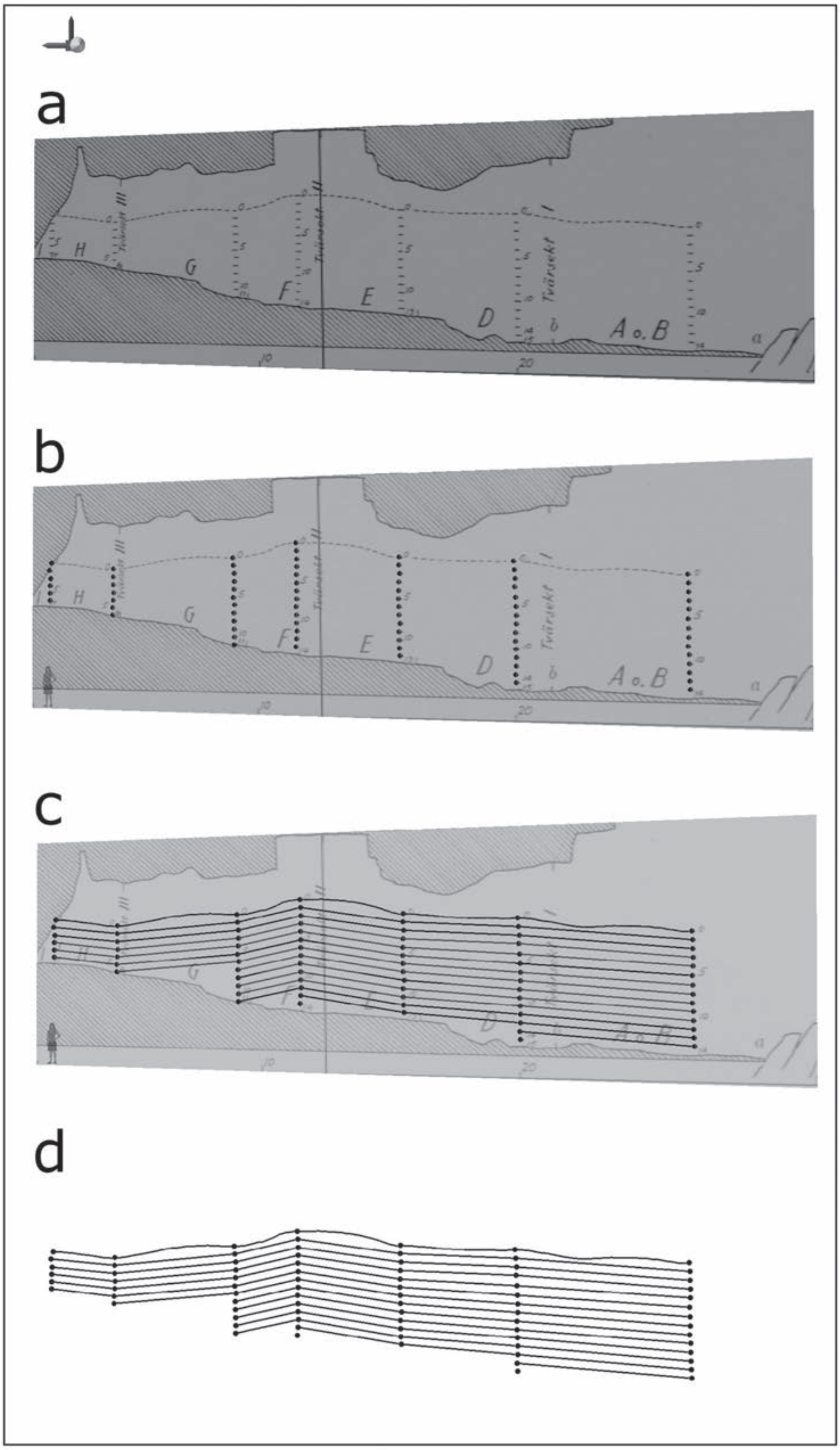

Figure 7. Workflow of data digitisation related to the archival profile drawing. The hand-written document has been digitally scanned and imported in Arcscene (a); then a 3D point shapefile has been created to mark all the intersection points between spit units and parcel boundaries (b); a further 3D shapefile has been added to connect the previously created points in order to obtain the exact interface lines marking the units as they were excavated based on the arbitrary method (c); finally the digitised profile has been created and set as a reference for starting the reconstruction of the sequence (d).

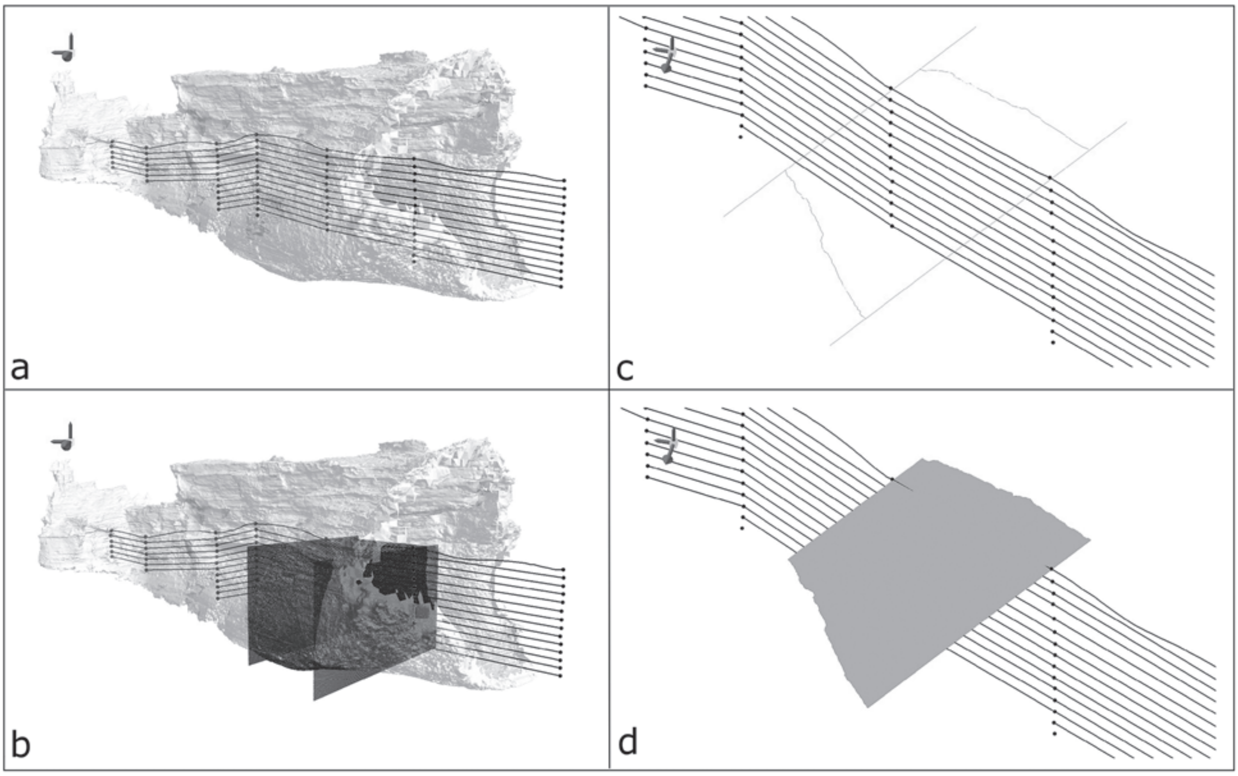

Figure 8. As a starting point of the stratigraphic sequence reconstruction, digitised profile drawing and cave multipatch feature class were used to define spit units boundaries along x, y, z coordinates (a). On a parcel basis (b), each unit's interface was employed to generate a plan that intersected the cave walls. As a result, the intersection polylines were generated and these were merged with lines originated from the intersection between vertical plans placed at each parcel's limit and the previously-described 'spit unit plan' (c). Each closed polyline defining each single 2 cm-thick sub-unit (15 of them were created to define one original 30 cm-thick spit unit) was then converted into a 3D polygon (d).

To cope with this issue, the decision was to divide each layer into fifteen smaller sub-layers, so as to apply the extrusion on each one of them, in order to cope with the wall's irregularity, by reducing the error rate due to the mismatching between the verticality of the extruding walls and the actual convexity/concavity defined by the cave boundaries.

As a result, the entire sequence of arbitrary layers was reconstructed with each unit made of 15 separate 2 cm thick volumetric units. In total, more than 7000 sub-sampling units were used to represent the whole sequence and each one of them was assigned with volume information (Figure 10). Still, some additional operations were expected in order to effectively use the volume values in relation to the original arbitrary layers excavated during the 19th century. In particular, relationships had to be set in order to link the multiple 2 cm thick sub-layers with their corresponding unit. This operation would have enabled users to easily calculate the whole volume value for each spit unit as a result of the sum between all of the sub-layers grouped and related by unit number. Calculating the volumetric values associated to each arbitrary layer is an undoubted advantage for any further analysis connected to the spatial configuration of the cave and its original stratigraphic sequence.

Preliminary results

As previously mentioned, this experiment is part of ongoing research in which a novel methodological approach has been tested with the purpose of generating new insights on the heuristic use of 3D in archaeology. In particular, the combination of advanced techniques of three-dimensional acquisition and the analytic potential of GIS platforms allowed archaeologists to re-contextualise and re-examine old site documentation in order to obtain new information to be used in support of the interpretative process. Interestingly, archive sources already provided archaeologists with the opportunity to relate most of the collected artefacts with their original layers, but only three-dimensionality allowed an effective and almost complete review of the actual spatial location and reciprocal relation between the objects. As suggested by Harris (1989), the use of three and four-dimensional information is a crucial point in the process

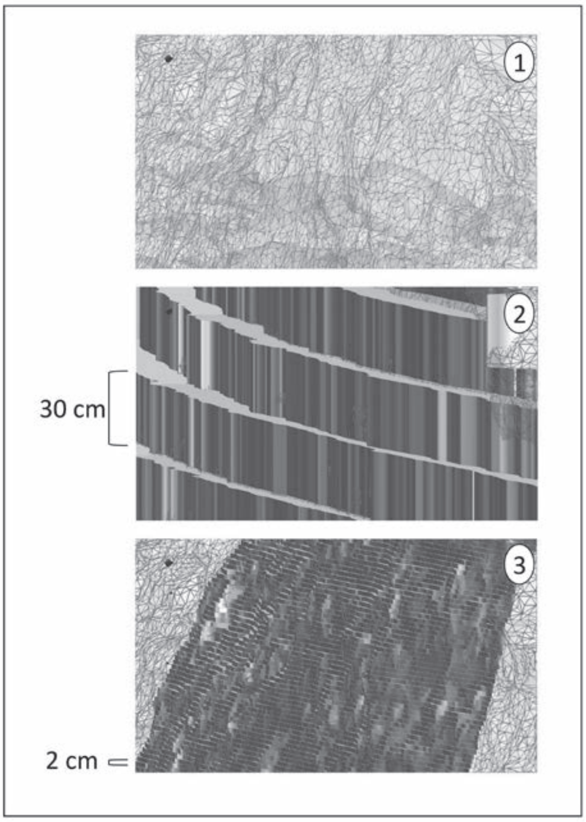

Figure 9. the reconstruction of volumes associated to the sequence has been obtained by vertically-extruding each plan previously defined. The starting idea of creating a single extruded volume for each 30 cm-thick spit unit gave us the misleading result of producing ‘coarse’ external boundaries (2) that were not matching with the actual cave walls (1), increasing inaccuracy and redundancy in the sequence volume representation. To cope with this issue, each spit unit has been divided by 15, creating 2 cm thick sub-layers whose reduced extrusion made the entire sequence model a better fit with the irregular shape of the cave walls (3).

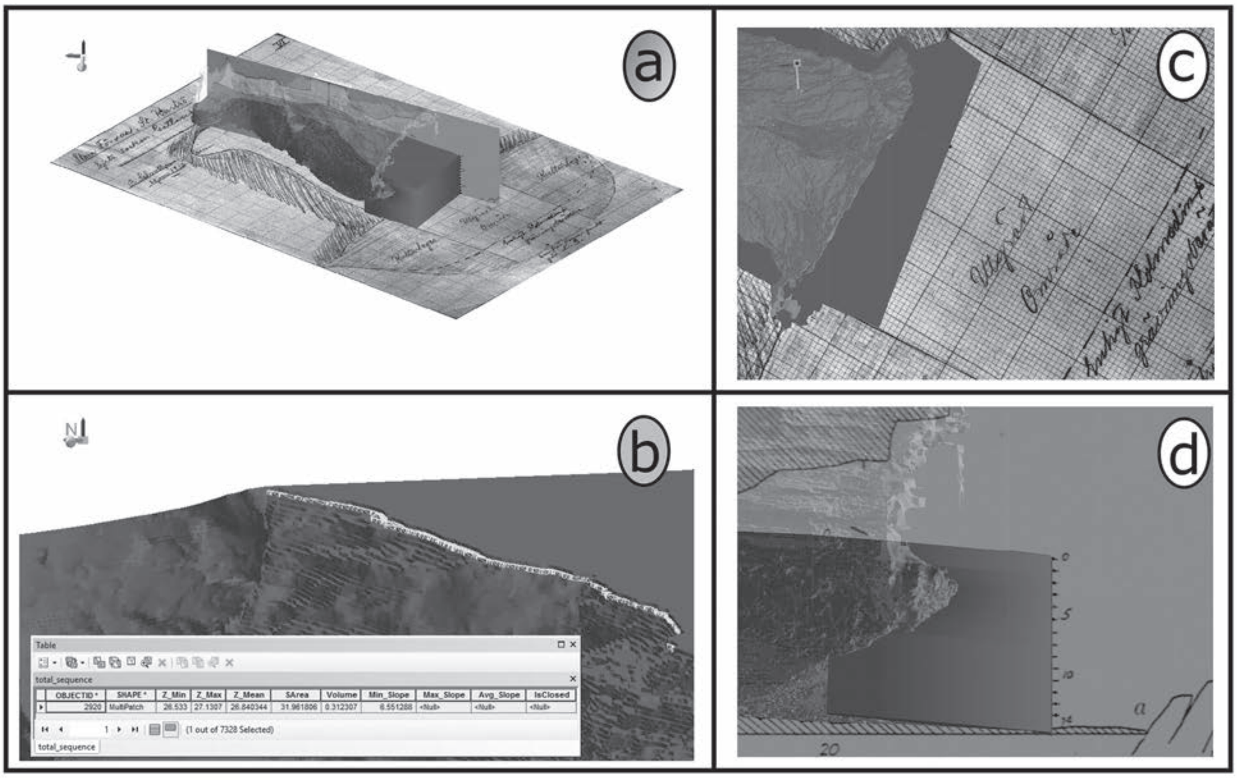

Figure 10. A three-dimensional sequence has been finally reconstructed based on combined information derived from old archival sources and the cave boundary 3D model (a); each spit unit is defined by 15 different single sub-layers, that identify independent volumetric units that have been grouped based on the unit they belong to through a database relationship (b); the portion of the sequence protruding outside the cave and whose walls were artificially cut by the excavators, has been finally reconstructed based entirely on plan and profile drawings (c, d).

of interpretation of an archaeological excavation and in this sense the adoption of a 3D GIS platform can further improve the quality of the research on old archive data. The obtained results show that it is possible to spatially reconstruct the original sequence of arbitrary layers as they were described by archaeologists and to quantify, with a certain degree of accuracy, the volumetric values associated to each unit. In terms of relative chronology of the cave, the first important point is the possibility to show the reciprocal position of the layers in the space and to evaluate the deposit formation order. Additionally, by linking the artefacts information to the layers it will be possible to study the distribution of particular classes of objects throughout the entire sequence. By combining the number of artefacts with the volume value associated to each unit, additional information will be provided in the form of density maps, which might be used to better understand the presence of patterns that can generate some insights on the different phases of habitation of the cave. In brief, the research conducted so far has shown enormous potential in terms of data representation and significant advances in the investigation strategies of prehistoric caves now offered to archaeologists.

As for future research, GIS-based tools will be employed to make a quantitative assessment of the volumetric value associated to each arbitrary layer and to carry on a precise computation of the collected artefacts in order to generate three-dimensional maps of density that will allow us to better detect and observe patterns of presence/absence associated to specific categories of artefacts, that might be put in connection to the different phases of inhabitation of the cave.

Acknowledgements

This research activity was generously supported by the Berit Wallenberg Foundation, Swedish Research Council and Palmska Foundation, and by the Birgit och Sven Håkan Ohlssons Foundation, The authors wish also to thank the Humanities Laboratory and DARK Lab, Lund University, for the opportunity to use instruments and facilities in order to perform this experiment.

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Les gestes retrouves: a 3D Visualization Approach to the Functional Study of Early Upper Palaeolithic Ground Stones

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Abstract

The paper presents an innovative approach to the identification and characterisation of use-wear traces on Aurignacian ground stones (GSTs) which were used to process plants in order to get staple food. It is based on the integration of qualitative visual analysis of the micro-topography of stones' surfaces, in order to preliminarily delineate functional areas, by means of 3D documentation, roughness analysis, macrophotography and RTI. Once outlined, such areas are further investigated with digital microscopy, Scanning Electronic Microscopy, residues analysis, etc. Consequently, data (2D images, 3D models, analytical measurements, etc.) are merged into a single data management system, based on current ontologies such as CIDOC-CRM (and its relevant extensions — CRMdig and CRMsci). They are then visualized into a single geo-referenced system based on the 3D model of the stones. Such a study is essential in reconstructing ancient dietary habits of humans at a crucial stage of human colonisation in Eurasia.

Keywords: 3D micro-topography, use-wear analysis, data integration

Introduction

Prehistoric hunter-gatherers subsistence strategies have been widely examined, and diet breadth has become a significant issue to evaluate costs and benefits for human groups exploitation within a given territory. According to recent advancements in collecting and analysing evidence on food resources entering the Palaeolithic diet, the role played by vegetable food processing for producing flour was recognised as a systematic practice since at least the beginning of the Gravettian, some 25,000 years ago (Aranguren *et al*., 2008; Revedin *et al*., 2010). This is shown by previous results from the Gravettian sites of Bilancino (Italy), Kostenki 16-Uglyanka (Russia), Pavlov VI (Czech Republic) and Paglicci cave (Italy) (Revedin *et al*,. 2015). One grinding stones and several pestles recovered at these sites have been used to process plants rich in starch, such as Typha (bulrush), apparently for flour production, which can be easily transformed into high–energy staple food. Additionally, flour is storable and movable, and after cooking it is possible to obtain a 'porridge-like' soup by adding water, which might have been the most appropriate way to help digesting carbohydrates.

The highly perishable character of plant remains makes these types of evidence very scarce and difficult to identify and retrieve; thus they are quite poorly documented for most of the Palaeolithic (Mason *et al*., 1994; Hardy *et al*., 2001; Lev *et al*., 2005; Aranguren *et al*., 2008; Revedin *et al*., 2010, 2015). Moreover, un-modified manuports used by Early Upper Palaeolithic (EUP) people to process plants food are not easy to identify in the archaeological repertoire. At a first glance they may seem like regular stones/pebbles. It is probable that an unknown quantity of such items were neglected in the past; instrumental in this sense is the fact that Russian archaeologists often collected and archived such items found in various excavations and this is precisely one of the reasons why our investigation started with material collected by Russian museums. New methods and approaches are also needed to document highly perishable plant-processing remains from such remote periods.

We propose an integrated methodological approach, based on macro and micro investigation of the 3D geometry of ground stone tools, centred on the analysis of their surfaces' roughness and related use-wear traces. Functional areas are first delineated by changes

Figure 1. Grinding stone from the Surein I, level III (Vekilova) or F (Demidenko).

Figure 2. Pestle no.72 from Kostenki 14 (Markina Gora) Cultural layer III, horizon in vulcanic ash.

in surface roughness patterns and further investigated microscopically at various magnifications, in order to isolate and describe use-wear traces. Analyses on the residues associated to wear-traces are ongoing. Causal association between residues of plant remains and use-wear traces is an additional phenomenon investigated. Aurignacian ground stones have been chosen as a case study, in order to assess the antiquity of the related dietary strategy of processing starch-rich plants for the production of staple food. Our preliminary results indicate that plant processing was a shared practice among Anatomically Modern Humans (AMH) since their earliest arrivals in Europe.

The case study

The material analysed in the study presented herein originates from the Eastern European sites of Surein I (The Crimean Peninsula, Vekilova, 1957; Demidenko *et al.,* 2012) and Kostenki 14-Markina Gora (Don river valley, Sinitsyn, 1996, 2014, 2015), from well attested and documented EUP layers, which have been recently radiometrically dated. It consists of one large grinding stone from Surein I (Figure 1) and seven ground stones from Kostenki 14-Markina Gora (Figure 2): three from layer III and four from layer IV.

The oldest occupancy at Surein I, from where the analysed grinding stone originates, is an Aurignacian horizon (level III according to Bonch-Osmolski excavation, Vekilova, 1957, or Level F according to Demidenko, 2014). The age of the cultural layer Fb2 date back to 33.5–35.4 ka cal BP on the base of the radiocarbon dates: 30,910 ± 240 (GrA-46552) (cal: 35,006 ± 368) and 29,950 ± 700 (GrA-46552) (cal: 34,130 ± 647) (Demidenko, 2014; Demidenko *et al.*, 2012). New AMS radiocarbon dating on the faunal remains from the same layer where the GST was retrieved is ongoing (III, Vekhilova, 1957, fig. 34, 37). Radiocarbon dates on charcoal for cultural layer III and IVb at Kostenki 14 give respectively a frame of 35.1–36.4 ka cal BP and 41.1–42.2 ka cal BP (Sinitsyn, 2015).

Since both the Surein I and the Kostenki 14 ground tools are associated with the lower levels of their corresponding sites and attributed to early AMHs, the new set of radiocarbon dating brings the evidences for the beginning of the processing of plants for starch-rich food production back to ca 38 cal ka BP, documented by use–wear traces (see below). The implication is that the systematic utilisation of compound technologies for plant food processing is relevant to early modern humans, and can be associated with their earliest Upper Paleolithic settlings.

An integrated 3D visualization approach to functional studies

The Surein I material has been analysed in situ at the Department of Archaeology of the Peter the Great Museum of Anthropology and Ethnography, St. Petersburg, Russia, in June 2015. After a preliminary survey with a Low Power Microscope, the material was 3D documented with a Next Engine laser scanner set at its highest resolution. Consequently, moulding has been applied (Provil L Bayer) in order to obtain a replica of the surface modification, to be further analysed off site in other laboratories and with various other instrumentation (Digital Microscopy — HIROX 8700, SEM-EDAX, FESEM). Furthermore, each mould was 3D documented using photogrammetry, with a NIKON D3X digital camera. During the months of September and December 2015, the stone materials of Kostenki 14 and the moulds obtained from the Surein I grinding stone were analysed at the Cyprus Institute, using a high-resolution structured-light scanner, RTI imaging, large-format photomacrography (to be processed at a later stage) and digital microscopy.

Moreover, surface investigation was performed both at macro and micro levels. At macro level we noticed deliberate (human inflicted) modifications on the object's surface, identified as functional areas, which were thoroughly investigated at micro levels (digital microscopy 20X to 2500X, SEM/FESEM) for the isolation

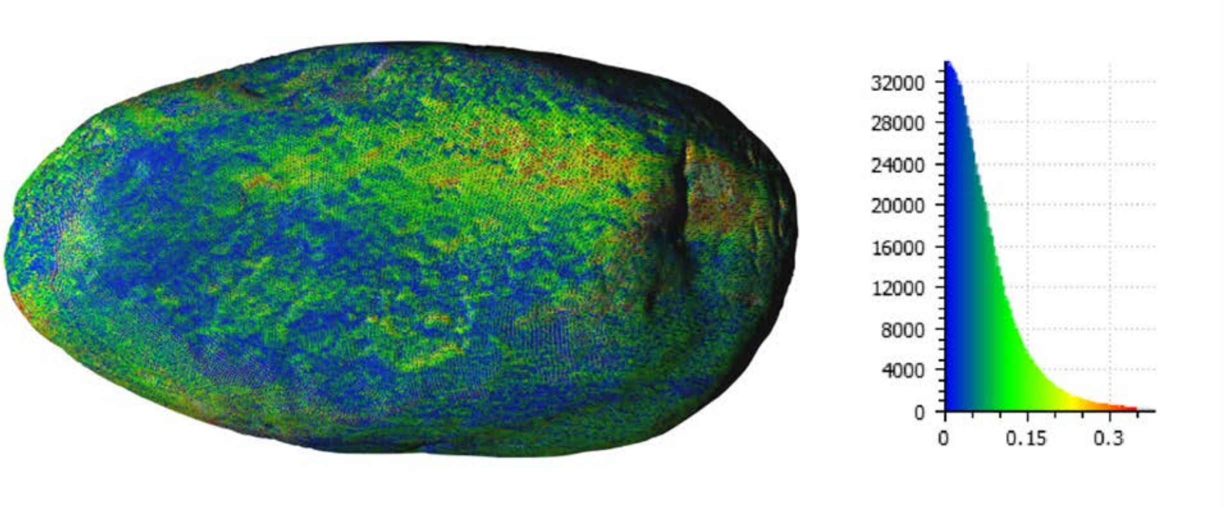

Figure 3. Rugosity analysis of Surein I grinding stone (cloud compare software) — blue areas apparently correspond to functional areas of the stone.

of use-wear traces, eventually associated with starches, identified on content cleaned from Kostenki 14 pestles using an ultrasonic tank, a centrifuge and the pellet analysed with optical microscopy techniques (ongoing).

Such an analysis produces heterogeneous data, both digital and analytical, which has to be conveyed into a single data investigation and management environment. The 3D model of each stone allowed the visual inspection of data, using various shadowing techniques, rotation and investigation under different angles, and accurate measurements as well, such as mathematical transformations (Rugosity analysis) (Figure 3) or causality of associations (starches and use-wear traces). The digital model served as a geo-referenced basis for the geo-location and mapping of obtained data. Microscope images were positioned on the 3D model in a CAD system; each magnification was considered as a different layer. A data management system, based on CIDOC-CRM and its related extensions (CRMarcheo for the provenance of the archaeological material, CRMdig for the digital data and CRMsci for the analytical measurements) was created accordingly to archive the data produced, along with the analysis and interpretation.

The main steps of the 2D and 3D visualization analysis presented in this paper are described below:

- Preliminary surface investigation with low-magnification microscope, overall 3D scanning and moulding selected areas.
- High-resolution visual and metrical documentation: 3D geometry, RTI and rectified photo-macrography.
- Rugosity analysis of the stones' surfaces, in order to identify human inflicted anomalies (both due to the use and post depositional modifications), relatable to plant processing; performed using roughness analysis in the cloud compare software and Meshlab function of colourising curvatures (several tests are currently performed, using different curvature types and parameters).
- 3D documentation of moulds. These were 3D documented using photogrammetry. Values were inversed along the Z-axis, in order to correctly represent the surface's micro-topography and to be re-located virtually along the surface of the stones.
- Mapping the digital microscopy images within a single geo-referenced system based on the 3D model of the stones and embedded within a CAD environment.
- Positioning of measurements results (graphs, tables, etc.) at the measurement point within the CAD system.
- Measurements of the area of trace marks and characterisation of their shape.
- Clustering these marks with associated starches.

a) Microscopy applied to the surface analyses

Microwear analysis was carried out in situ at the Institute for the History of Material Culture in S. Petersburg, Russia (Optical Microscopy), in the laboratories of The Cyprus Institute (Digital Microscopy) and at the Nanyang Technological University (NTU) in Singapore (SEM and FESEM). Optical light microscopy was carried out by means of binocular MBS 3 (up to 88X) and a metallographic microscope with 4 lenses (50X–500X) equipped with differential interference contrast (DIC) prisms (also known as Nomarski [NIC] prisms), equipped with a Canon EOS 400D camera and Helicon Focus Pro (©HeliconSoft) software, which was used for the treatment of images (Plisson and Lompré, 2008).

Figure 4. Kostenki 14 pestle (original surface) Metallographic microscope image of crystals with smoothed edges. Some residual blackish component has been evidenced (100).

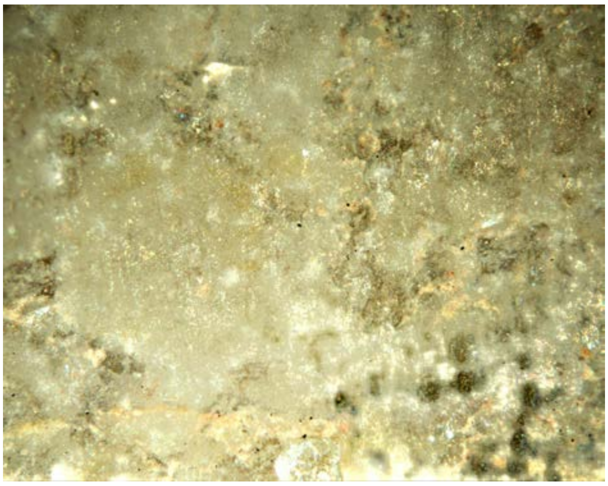

Figure 5. Kostenki 14 pestle (original surface) Metallographic microscope image of parallel clustered striations on a heavily warned crystal (200).

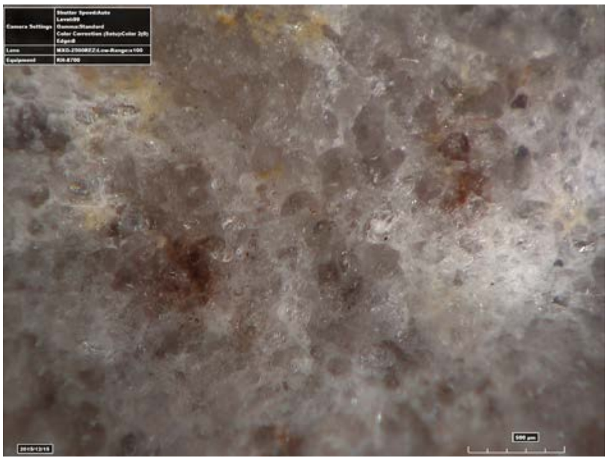

Figure 6. Kostenki 14 pestle (original surface). The quartzite crystals popping up the surface appear worn and flattened because of the abrasion caused by the grinding and crushing action in order to produce flour out of rhyzomes.

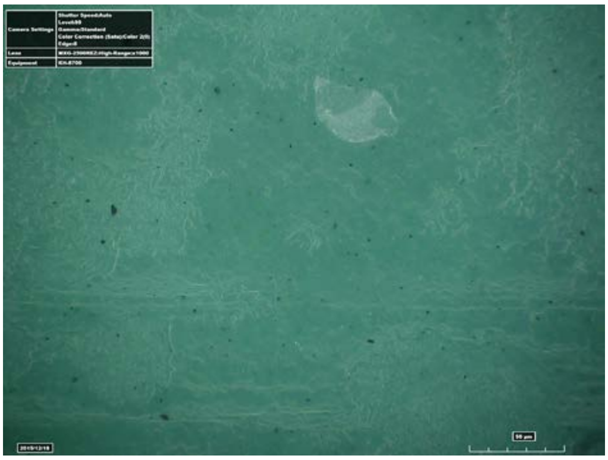

Figure 7. Surein I grinding stone (mould). Alignments of striae are interpreted as use-wear traces triggered by the process of grinding plants material. Striations are associated to polished areas and both the features can be related to USOs processing.

It allows for building images from several taken at different depths of field (Figure 4 and 5).

The second stage of identification and description of use-wear traces was carried out through the combined potential of the Digital Microscope (Hirox KH–8700 at The Cyprus Institute) and Electron Scanning Microscopes (SEM and FESEM at NTU, Singapore). The Hirox KH-8700 has a multi-viewer function that allows easy inspection at various angles. The device has two lenses: macro MXG 2016Z, working as a stereomicroscope at lower magnification; and MXG 2500REZ, working as a metallographic microscope (up to 2500X). A fully focused image can be obtained

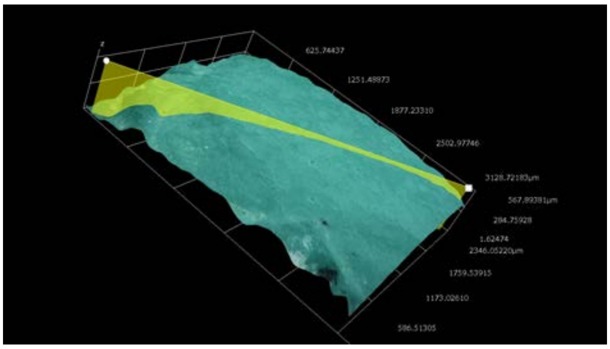

Figure 8. Cross-section of a polished area on Surein I grinding stone (mould).

instantaneously by compiling images at different focus depths and it can generate a 3D digital model that enables efficient observation of the surface from various angles. This device has proved a very effective tool for distinguishing between the worn crystals embedded in the matrix of the large cobbles. With the digital microscopy we studied both moulds of the stones and a selection of the original Kostenki 14 materials (Figure 6 and 7). Images were acquired at various magnifications, from 35X to 2500X.

Cross section enabled further geometric characterisation of use-wear shapes and profiles (Figures 8).

Investigation with Scanning Electron Microscope (both SEM-EDS and FESEM) allowed us to confirm the presence of use-wear and associate organic residues (possible starch) on the surface of the moulds.

SEM and FESEM are both electron-scanning microscopes. They differ in the resolution because in the latter the gun emits the electrons from a much smaller area, thus the spot diameter compared to the thermionic emission is reduced and the energy spread is smaller. The FESEM eliminates (some) aberrations, allowing for sharper images. Both microscopes can help with chemical make-up of the sample by performing elemental analysis or characterisation of a sample (Energy-Dispersive X-ray Spectroscopy). A WDS (Wavelength Dispersive X-ray Spectroscopy) associated with a FESEM (Jeol JSM-6700F available at NTU) has a much finer spectral resolution than EDS/EDAX because it is using diffraction on single crystals and it analyses one element at a time, making it possible to separate raw data into spectral components (wavelengths). Both the facilities have been applied to the study of the Surein I and Kostenki 14 ground stones (Figures 9 and 10).

At micro and nano scale the conventional microscope investigation of wear-traces (integrating optical and digital microscopy with SEM/FESM-EDS) are combined with residues extraction by sonication — both from the archaeological stones and the moulds — in order to have an accurate localisation and consistent overlapping with wear-traces, and eventual organic residues (e.g. starches and phytoliths). The use of the three-dimensional imagery proved to be very effective when creating a 3D image that allows areal, linear and angular measurements of the traces.

b) Photogrammetry

Digital photogrammetry is a feasible and flexible solution, which allows the achievement of accurate results for systematic 3D surveys (Granshaw, 2014; Remondino *et al.*, 2014). For the present study, the

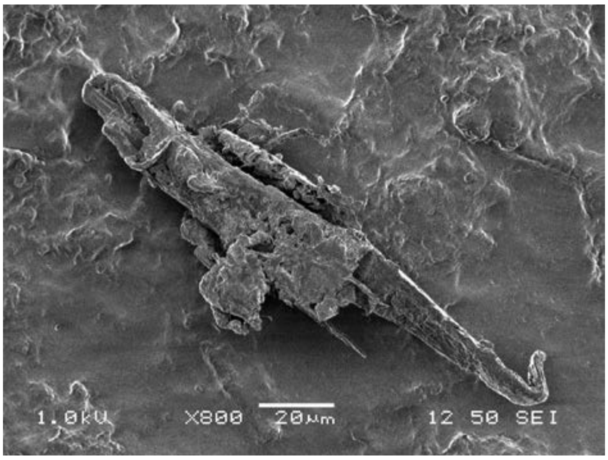

Figure 9. Surein I grinding stone (mould). The presence of residues is evidenced by FESEM.

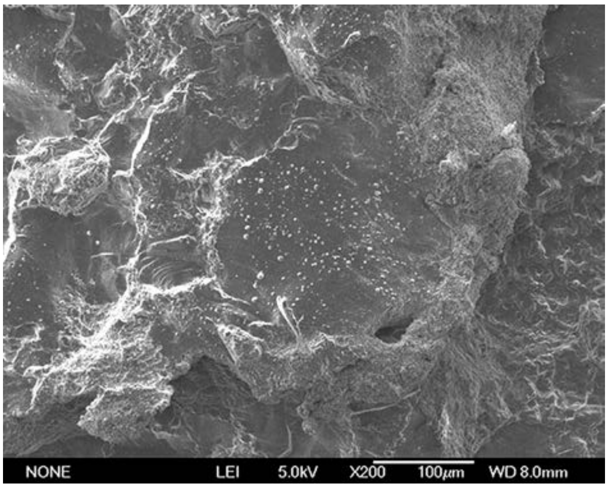

Figure 10. Kostenki 14 pestle (mould). SEM high resolution allows identifying polished areas on warn crystals associated with residues.

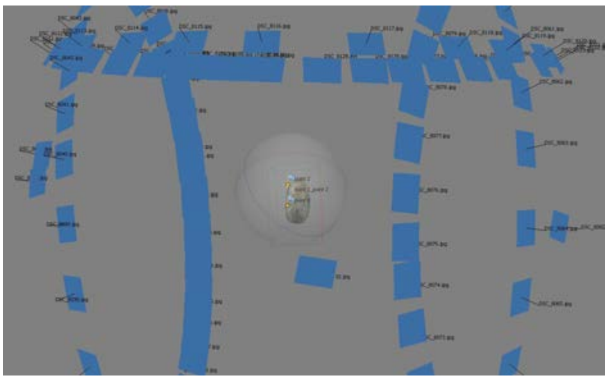

Figure 11. Photogrammetric Camera Network.

Figure 12. Point cloud (3694474 points) of Surein I grinding stone (mould).

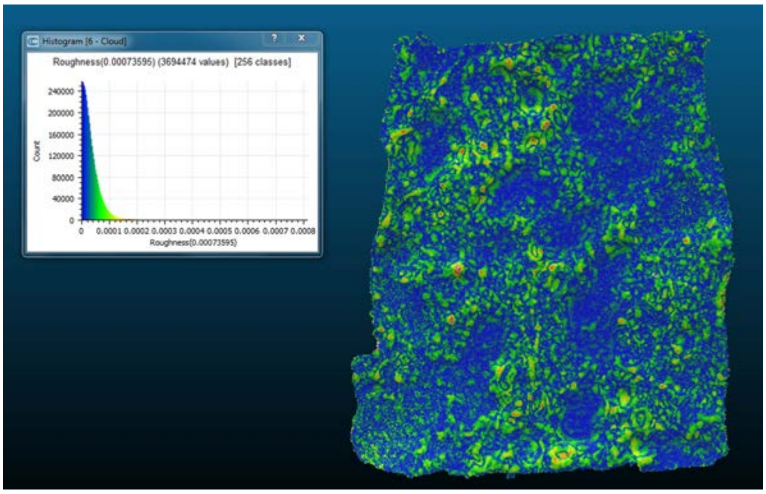

Figure 13. Rugosity analysis of Surein I grinding stone (mould).

main purpose was to digitise the Surein I grinding stone and the moulds, with the final goal of obtaining a high-resolution 3D model and orthophotos for further surface analysis and reliable measurements. In order to maximise the accuracy of the photogrammetric survey, camera calibration was performed to solve the internal parameters of the camera (focal length, principal point offset, as well as the three coefficients of radial and two of decentring lens distortion) (Remondino and Fraser, 2006).

The camera used was a NIKON D3X equipped with a 24 megapixel full-frame CMOS sensor (6 mm pixel size). The lens mounted was an AF-S MICRO NIKKOR 105 mm 1:2:8 G ED prime lens.

The Surein I grinding stone was placed over a rotating table with a neutral background yielding a distance camera–object of 95 cm. To fix the requirements of sub–millimetre accuracy for the 3D geometry, a photographic scale of 1:10 was selected. With such a scale, the ground sample distance (GSD) of the model was ca 0.05 mm. The camera's autofocus was disabled to avoid accidental changes of interior orientation parameters. A scaled dense point cloud of ~ 55 mil points was obtained (Figure 11). The same procedure was applied to the seven ground stones from Kostenki 14.

For the digitisation of the moulds, a proper camera network was planned *a priori* including convergent and rotated images (Fraser, 1984) with a baseline among them of 35 cm and an angle of 20 degrees. The objects, illuminated with photographic lamps, were placed over graph paper in order to scale the 3D models according to known distances. The images were automatically processed with Agisoft Photoscan. The extracted tie points were filtered to keep only well distributed, reliable points and to reduce the re-projection errors. Finally, a dense point cloud and a mesh model were created with a GSD of 0.04 mm (Figure 12).

Discussion

A primary goal of the on-going research described above is to identify use-wear traces on ground stones used to process plants food in Early Upper Palaeolithic, through an integrated approach. A first step is the delineation of functional areas, the assumption being that such surfaces display a different pattern of smoothness/rugosity, than un-used areas. Then the computing of a 'topographic' map of the stone surface is realised. The coordinates of each point on the 3D model (x, y, z) were compared with its neighbour point's coordinates along an imaginary common plane. Distances from the most common plane (defined as the plane with most points) were measured and false colours (blue — most common plane, red the farthest from it) were assigned along a linear scale (Figure 13). Obviously, such a 'colourisation' depends on the density of the point cloud, which in turn depends on the accuracy and resolution of the acquisition process and the margins of errors of the instrumentation used. One should also make sure that the distances between the points on the point cloud are smaller than the distance set for comparison between the locations of points. Moreover, it should be clear that such an analysis serves as a first indication of some 'anomalies' along the surface of the object analysed, and by no means quantitative in nature. Thus, it was assumed that 'smooth' areas (areas with most points in common along a single plane) are those suspected to be functional areas and where microscopic analysis should concentrate.

At this stage of research, it is very difficult to compute a quantitative analysis and comparison between various areas, considering *in primis* the taphonomic processes that affect any archaeological remains, and then the fact that the abrasion rate of a stone depends on several uncontrollable factors, such as amount of work invested in processing plants, the nature of processed material, the technique of processing, the type of ground stones etc. The ideal situation would be where one can compute a formula where the abrasion rate can be calculated according to the above factors (and others), and the relation and the causality between them. Apparently, experimental archaeology may provide only partial — even though valuable — answer to the above. However, since the formula is not known, and the contribution of each variable is unmeasurable as well, this again results in qualitative data. Nonetheless, for our purposes, the identification of anomalous surfaces (smoother than other un-used areas) sufficed to indicate a potential 'functional area', to be further investigated under the microscope. Indeed, such hypothesis was proven later on as it correctly identified areas where use-wear traces were isolated.

Further investigation requires a refinement of the methodology, looking into the optimisation of setting-up the parameters for analysis (how many iterations, minimum density of point clouds required, type of statistical transformation, algorithm for curvature analysis, etc.). The same is true for visualization matters — what is the desired range for the sizes of points to be shown, which rendering should be used and how data should be presented (point cloud / surfaces).

The digital processing of this complex data sourcing allows us to create a virtual stone tool that can be used as a visualization platform; a 3D portable document format for multimedia interactive tools, and one not just for scholarly use. The 3D shape and data that go with it turned out to be very appropriate, as the present paper is evidencing.

In the processing of different scales of data, 3D models become very useful, since the model can 'host' other kinds of data retrieved using other analytical techniques, such as light, digital and electron microscopy, residues analysis and other forthcoming data. At micro scales, the conventional microscope investigation of wear-traces (integrating optical and digital microscopy with SEM/FESM-EDS) is combined with residue extraction by sonication in order to overcome issues raised on the actual direct connection of residues with the utilized areas. The procedure developed in this study allows an accurate localisation and the consistent overlapping of wear-traces and eventual organic residues (e.g. starches and phytoliths). The use of the three-dimensional imagery proved to be very effective when creating a 3D image that allows areal, linear and angular measurements of the traces.

The final step of the project is devoted to museum accessibility and their mission to bring to broader audience the results of this cutting-edge research. Hence the research is also designed to bridge a quite common gap among analytical processing: the results and the means to make them available not only among academics but to the general public as well, in order to increase the awareness of the mission of collection keeping.

Conclusions

The surface investigation of the ground stones from Surein I and Kostenki 14 (III and IVb layer) confirmed that these manuports, firstly identified as simple stones/cobbles (Adams *et al*., 2009; Dubreuil *et al*., 2015), were used as 'ground stone tools'.

The 3D visualization integrated approach applied to functional studies of stone tools demonstrate the causal relation between use-wear traces produced by ryzhomes or roots being ground or crushed in order to extract starches, and the residues adhered to grinding stones and pestles. A systematic technology devoted to maximizing knowledge over plant foods greater dietary contribution to nutritional strategies — that satisfies the changing subsistence needs according to the settlement in new territories by AMHs — has been demonstrated to be a common practice in a vast geographical area (from southern Europe to Russia), and was a component of the food economy of modern humans who were just colonising Eurasia. The research is pointing out that plant food processing has to be considered one of the components of modern humans' technological breakthrough. Transformation, consumption and digestion of carbohydrates provided by starchy plants appears to be in the capacity of early waves of AMHs colonizing Eurasia.

Our preliminary data support lines of evidence for a systematic technology devoted to maximise nutritional strategies — that includes plant food processing — proven to be a common practice since at least the Aurignacian, thus some 10,000 years before the previous Gravettian evidences. The regular practice for plant food processing is documented by use-wear traces on ground stones — grinding stone from Surein I and pestles from Kostenki 14 — that can be associated with plant residues (starches, phytolites, fibers), thus proving this had an impact on the ability of modern humans to address the climatic changes over the

CI-HE4 (Heinrich Event 4). This behaviour is even more strategic when hunting large games became more problematic because of these climatic alterations.

The analysed materials show that the beginning of this practice is related to early AMHs colonisation of Europe, and it became a usual and shared behaviour among groups that were living in both Mediterranean peninsulas (Italy, Crimea) and more northern territories like the Don River. Maximizing plant foods contribution by bringing in new toolkits and technological enhancements might have helped AMHs outcompete Neanderthals, who went extinct few millennia after the new comers' waves — modern humans — reached Europe, around 38 ka cal BC (Longo *et al*., 2012).

Acknowledgements

The work described is supported by SUG grant (N. M4081669.090 2016-2018) NTU Singapore and partially by the EU funded project ARIADNE (http://www.ariadne-infrastructure.eu/).

We wold also like to thanks RFBR, grant 17-06-00319, according to which the chronological database is realized.

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Mieko Matsumoto and Espen Uleberg (eds) 2018. *CAA2016: Oceans of Data*
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
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Enhancing Archaeological Interpretation with Volume Calculations. An Integrated Method of 3D Recording and Modeling

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Abstract

Digital surveying technologies have nowadays found extensive application in archaeology, enhancing the quantity and quality of data collected in the documentation of the archaeological assets. Besides the great communicative qualities, 3D data stores precisely the geometric information of a scene, enabling calculations of area and volume. In this paper we present two case studies in which area and volume calculations (on data from 3D survey and on 3D data processed and modeled through the tools and the principles of Virtual Archaeology) have achieved consistent results for the research and archaeological interpretation. Moreover, the 3D modeling process creates virtual reconstructions that are essential to verify the likelihood of some hypotheses and represents a powerful means of communication for disclosure.

In the first case study is a rocky outcrop by the medieval archaeological site of Canonica di San Niccolò (Montieri, Italy) where the particular shape of the context was, at first, interpreted as a mine entrance. The integration of different data sources from the 3D documentation of the outcrop, the excavation and the geological analysis has allowed the 3D reconstruction of the original shape of the outcrop, which must have once looked like a wide rock shelter, and is today collapsed. This new interpretation was enhanced and confirmed by area and volume calculations, which have enabled the accurate quantification of the amount of space available for a living floor in the rock shelter.

In the second case study, the method was applied in order to study the relations between the collapsed parts of a productive building and the destruction layers in the deposit of an archaeological excavation. Without any archaeological comparison for this type of building, the volume of the layers was used to estimate the volume of the collapsed parts and to reconstruct in 3D the original height of the walls and their complete shape.

Keywords: photogrammetry, image-based 3D modeling, virtual reconstruction, volume calculation

Introduction

In recent years, the use of 3D recording technologies for the documentation of archaeological evidence has slowly become a widespread and consolidated practice. This is mostly due to several benefits that these technologies have brought into the documentation method, such as improved accuracy and precision in recording the geometry of the scenes, the possibility to record colours, the fast acquisition process on field, and the great visual and illustrative impact that 3D models have for communication purposes (Dellepiane *et al.*, 2013).

Among the many case studies on this topic, where the 3D model constitutes an accurate and effective data type for recording archaeological evidences, only a few provide examples of the employment of 3D models for analytical purposes. This innovative research line recognises the 3D model not only for the great illustrative potential, but also as a type of data that stores particular information and that must be analyzed with specific tools. Some of the most significant examples that have influenced the development of this research, are those where 3D data is used to study the statics of the walls of buildings for conservation and restoration purposes (Campanaro *et al.*, 2015; Arrighetti, 2015) or to calculate volumes from irregular shaped surfaces, such as archaeological evidence (Lieberwirth, 2008; Magnani and Shroder, 2015). Moreover, a 3D model recorded through appropriate technologies and correct procedures, constitutes a reliable basis in terms of accuracy of the geometry, for virtual reconstructions using the tools of 3D computer graphics modeling (Dell'Unto *et al.,* 2013).

Virtual reconstructions have nowadays gained increasingly scientific value within research as a support tool for formulating hypothesis and testing interpretations. In addition to its original purpose, which is to communicate archaeological interpretations in an effective and direct way, today the virtual reconstruction is used primarily as a discussion tool. We should consider the reconstruction as a reiterated workflow, where every step is repeated recursively until the proposed model has been approved and

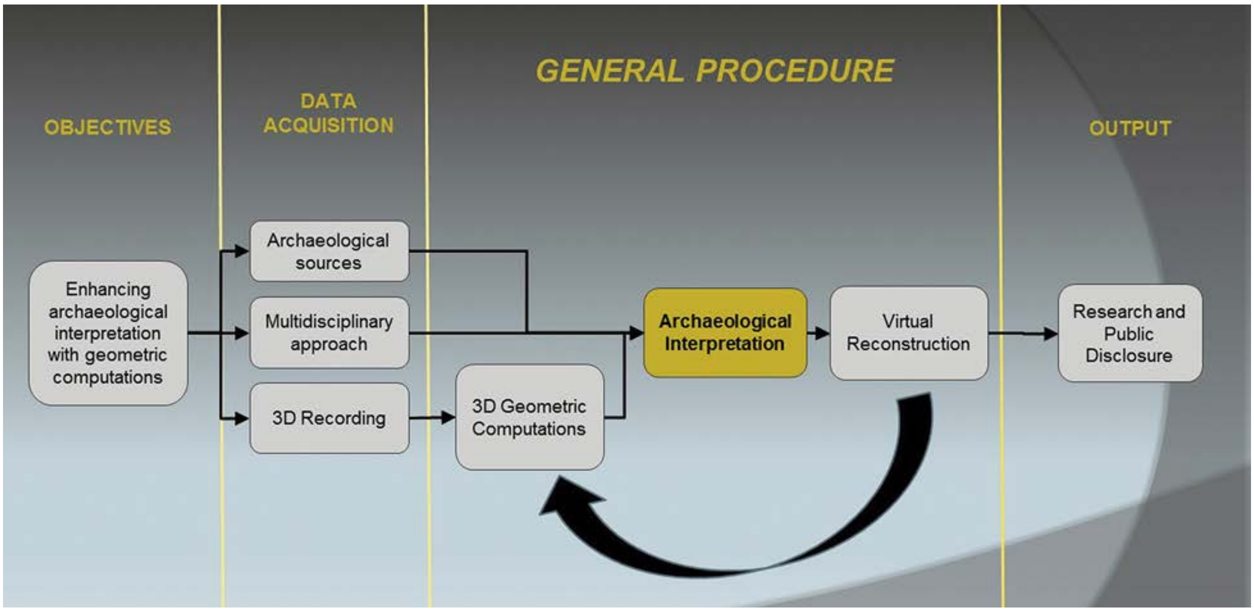

Figure 1. Geometric computations provide additional information that contributes to the archaeological interpretation. These computations can be performed both on the data collected in the field and on the data elaborated with the tools of the virtual reconstruction.

evaluated the most reliable, considering the data and the knowledge available at that stage of the research (Ferdani and Bianchi, 2016). The reconstructed model is both the final step of the workflow but also an intermediate step, because it becomes the testing ground upon which it is possible to perform measurements and calculations. The data produced are then gathered together with the other sources to create a more solid basis on which to adjust and calibrate the hypothesis.

Based upon these studies, this article presents two case studies where geometric computations performed on 3D data constitutes an additional source of information for the research process and contributes to the definition of more reliable and accurate archaeological interpretations. Besides the great qualities as a powerful means of communication, the models obtained with the virtual reconstruction are mined as a source of geometric information as well as the 'raw' model obtained from 3D recording in the field. By combining and comparing the measurements performed at various stages of the elaboration, it is possible to deduct scientifically accurate information for verifying the reliability of reconstructions and improving the quality of the interpretation.

Methodology

The following schema summarises the procedure adopted for the two case studies presented in this paper (Figure 1). For all the reasons specified above, a 3D recording campaign is carried out for documentation purposes. An image-based 3D modeling technique was chosen from among different technologies, after consideration of the results obtained in previous direct experiences with 3D recording technologies (Poggi, 2016) and in many papers about this topic (De Reu *et al.*, 2014). In particular, Photoscan (v.1.2) from Agisoft LLC was evaluated the best choice among many software options of the same category because of the reliability of the results and its ease of use. The software suits the needs of the research: to obtain 3D models of irregular shaped surfaces with a high geometric precision and colour information; to enable a survey campaign to be performed in compatibility with the timing and method of the archaeological fieldwork; and to use equipment affordable within the limit of the excavation funding.

The 3D recording campaign was supported by a survey campaign, carried out with a Leica TPS700 total station. Markers are placed inside a selected area before the recording process begins and their position is measured to obtain the coordinates along the three axes. These points are then used to scale and align each 3D model in a local coordinate system, in order to keep the spatial relationships unaltered among the different 3D models within the virtual environment.

Once the models are scaled and aligned, their geometric properties can be calculated. Using management and modeling software, like Blender, CloudCompare or related software families, it is possible to easily obtain the area of the surfaces or, in the eventuality of closed surfaces, the volume of the objects. Moreover, the interaction of different 3D models allows additional spatial analysis to be performed, for example calculating the volume delimited between two separate surfaces. In the virtual environment, the models are browsed in three dimensions from different perspectives thus enhancing the perception of the assets from different points of view. Specific tools facilitate the measurement of the distance between the points of the model in three dimensions thereby permitting the extraction of orthophotos and cross-sections automatically.

The geometric information gains importance within the interpretation process for it is obtained with scientific tools and methods, which converts the information into objective data. The strength of the virtual reconstruction is that it keeps the same geometric accuracy of the 3D models but adds several levels of interpretation. Virtual reconstruction has the potential to occupy the role of a visual platform where ideas and hypothesis are shaped, allowing exploration of the model in three dimensions and the use of analytical tools. The reconstruction is both the final product of the process and, at the same time, a source of geometric information, used to test and prove the reliability of interpretation.

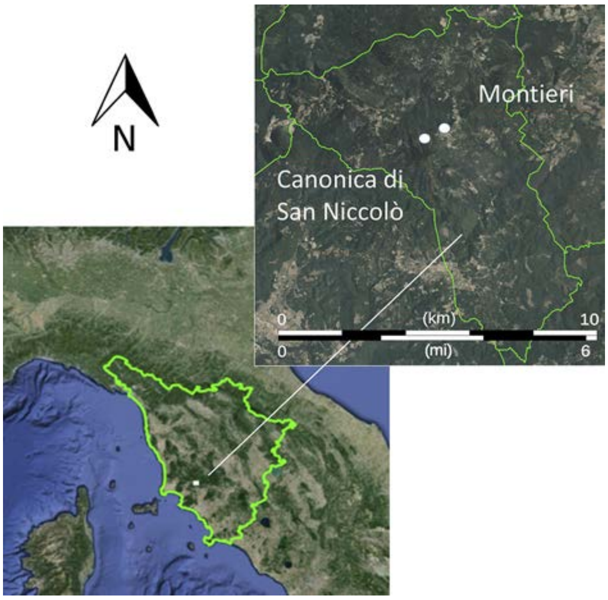

Figure 2. Montieri and its territory.

First case study: Canonica di San Niccolò

The outcrop and the area

The archaeological site of Canonica di San Niccolò is located near the medieval town of Montieri, in the territory of Colline Metallifere, southern Tuscany, Italy (Figure 2). The town and the surrounding area grew rapidly in the 12th century under the influence of the Bishop of Volterra, who promoted mining activities in the area for the extraction of silver. An archaeological excavation has been conducted by the University of Siena since 2009 on the remains of an ecclesiastical complex with a particular type of church that has six apses, which was occupied between the 9th–10th

Figure 3. The archaeological site of Canonica di San Niccolò. Top view from a gas balloon. Photograph by Paolo Nannini, Soprintendenza Archeologica della Toscana.

centuries and the end of the 14th century (Bianchi *et al.*, 2013) (Figure 3).

A few meters south–east of the archaeological site of Canonica di San Niccolò, on the northern slope of the Poggio di Montieri hill, there is a rocky outcrop that, due to its morphological characteristics and its proximity to the medieval buildings of the site, has since the beginning drawn the attention of the archaeologists (Figure 4).

Located in the middle of this outcrop there is an opening which is 3 meters wide at the entrance and progressively narrows towards the inside, and it is surrounded by two rocky walls of approximately 5 meters in height (Figure 5). At first, this outcrop was interpreted as a mining entrance, one of the many evidences left behind by the intense mining activities that were conducted in this region during the middle ages and that have been well documented by historical sources and archaeological fieldwork (Dallai *et al.,* 2012). However, in this case, clear evidence for such usage has never been retrieved from the archaeological investigation of main buildings of the Canonica, therefore a dedicated interdisciplinary study, which included archaeological and geological analyses, was conducted on the outcrop in 2014 in order to better understand its nature.

Preliminary investigations

The geological survey of the site found discrepancies in the orientations of the stratigraphy of the layers between the rocks forming the left limit of the entrance to those on the right. The stratigraphy of the right part of the outcrop is consistent with what we know geologically of this territory, whereas the left one does not. From this outcome, it has been possible to assess that the left boulder is not in its original position, but that, at a certain point in the past, it fell apart from the top right side of the outcrop. During this movement, the rock made a rotation of 20° both in the horizontal and vertical plane (Figure 6).

A small excavation was conducted in the area in front of the entrance of the outcrop owing to the need to find any anthropic element that could help in the development of hypotheses concerning the origin and the use of this formation during the medieval period. Furthermore, another intention was to understand better the formation of the outcrop, and additionally to date the event of the rock detachment. This excavation, conducted in a 2 × 4 m trench below the initials dirt layers that abut the boulder, initially discovered a flat layer made of stones of small dimensions that suggest, without any doubt, some sort of habitation of this area. Interestingly, this layer was seen to continue below the boulder on the left side of the entrance, but it abuts the right side.

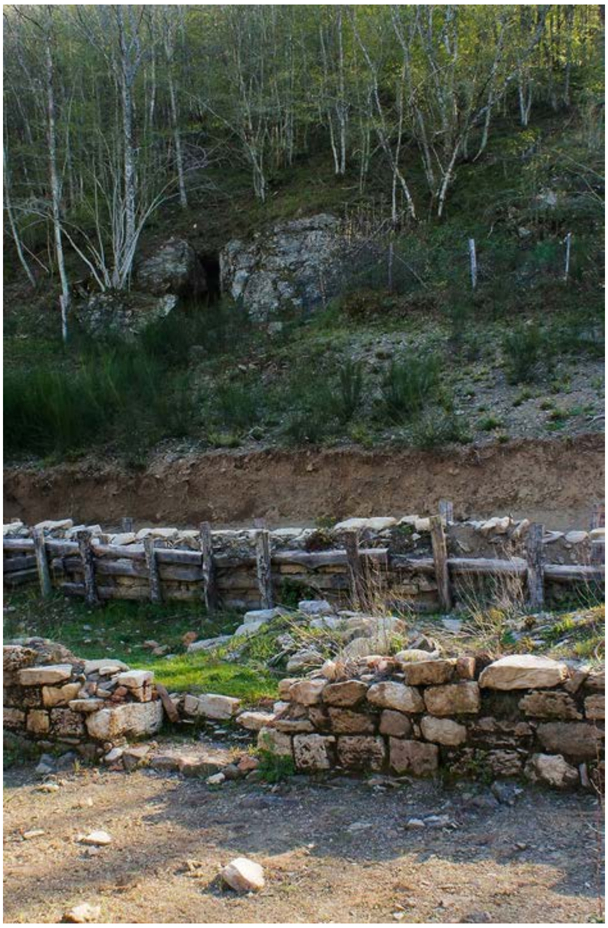

Figure 4. View of the Poggio di Montieri hill from within the archaeological site of Canonica di San Niccolò. The outcrop is located 18 meters south of the site and 10 meters above the ground level of the buildings.

Figure 5. Front view of the opening of the outcrop. On the left, the boulder detached from its original position; on the right, the natural rocky formation of the hill.

Figure 6. Rose diagram (azimuth 0–360°) of the number of features along a certain compass direction within a given range of angle. Station 1 is measured on the right part of the outcrop, Station 2 on the left. There is a concentration of measures around 200° for the Station 1 and around 230° for the Station 2 (Diagrams courtesy of Dr. Maurizio Negri).

This area is known to be susceptible to rockfalls and small landslides that have significantly altered the morphology of the hills. Therefore, the left boulder, as also highlighted by the geological survey, is in a secondary position after a collapse that is dated after this first prepared ground surface. About 1 m underneath this stratum, another level floor with similar characteristics has been discovered. From the deposit between these two prepared ground surfaces, a metal piece was found, which was identified as a part of a typology of local armor called *corazzina* that is dated at the second half of 14th century (Scalini, 2004).

The excavation made clear the chronology of the habitation of this outcrop, which happened before the collapse that detached the upper part of the rocky formation and that made it fall into its modern position, and within a time contemporary to the frequentation of the site of the Canonica (the lower stratum is dated before the 14th century).

3D recording and modeling

This collapse altered extensively the morphology of the context and partially destroyed the prepared ground surfaces, preventing us from identifying their original extension. Therefore, it was necessary to select a non-invasive methodology to reconstruct the context in its original morphology so as to design and test new hypotheses that could have explained the purpose of the habitation of this context during the lifetime of the ecclesiastical buildings in the middle ages.

Due to the difficult location of the outcrop, on a very steep slope of the Poggio di Montieri hill, and the irregular morphology of the rocks, the Image-based 3D modeling technique was evaluated as the best recording choice to obtain the 3D documentation in a short period of time and with relative ease, requiring only a handheld camera and steady feet.

The photographic acquisition campaign was performed with Nikon L120 Bridge camera, equipped with 14 Mpx sensor and a Nikkor 21X Wide Angle lens (25–525 mm). Pictures were taken moving around the outcrop in order to frame the many facets of the irregular shape of the rock from different perspectives, collecting at the end about 300 photos. The set of photos was then imported into Agisoft Photoscan software for the elaboration process, which can be summarised as follows.

As a first step, the ‘Align photos’ tool estimates the camera parameters and extracts a defined number of key points from each photo. The key points are then used to compute the camera positions and to build the structure of the scene in the form of a sparse point cloud. The tool’s accuracy was set to ‘high’ to obtain the highest quality possible. The sparse cloud is then scaled and aligned in the tridimensional space using the control points recorded in field with the total station. Each point is defined with a point ID and x, y, z coordinates, measured in the same local topographic system used in the archaeological site. Inside Photoscan, each control point is assigned to the corresponding marker visible in the photos. In addition to the scaling and the alignment of the point cloud, this step enables the optimisation of the camera alignment, in order to correct the reprojection errors of the initial alignment and to improve the accuracy of the final 3D model.

From the sparse point cloud, a dense cloud is elaborated with the ‘Build Dense Cloud’ tool by expanding the

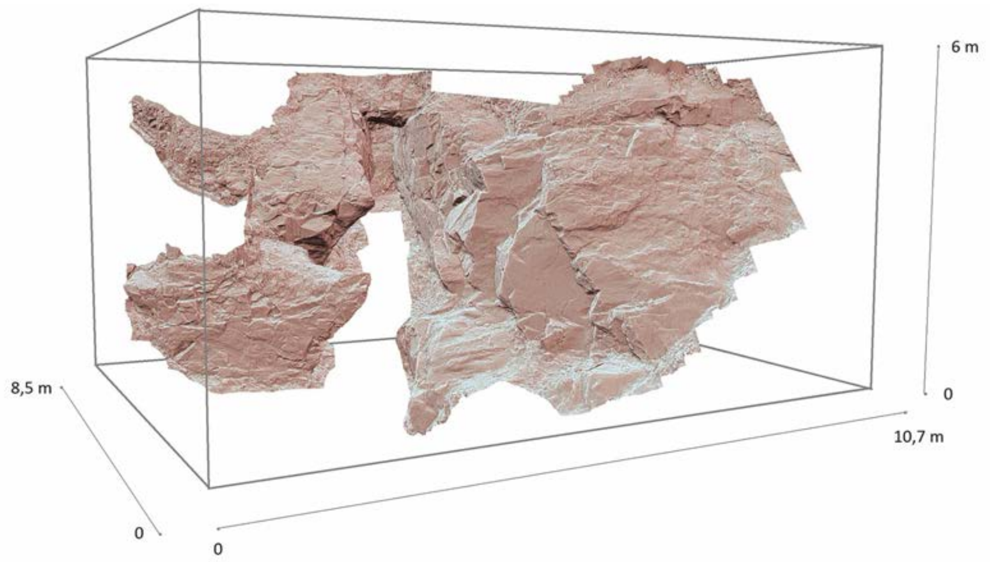

Figure 7. 3D model of the current shape of the outcrop with shading for the enhancement of the features.

relationships established for the key points to the pixels nearby. The dense cloud is then elaborated into a 3D mesh, in which triangular faces are used to interpolate the points of the cloud, creating a continuous surface. The colour information is stored as a texture file and projected on the model.

Due to the large quantity of photos and the considerable number of points obtained at the end of the alignment, the project was split into four chunks to be processed separately. This step lightens the processing and improves the quality of the final result. Once the models were completed, the chunks were merged together and the 3D model of the entire outcrop resulted in a 60 million polygon mesh with four textures of 16Mpx of resolution (Figure 7).

The objective of the research was to recreate inside the virtual environment the original morphology of the rocky outcrop in a time before the collapse, which dramatically altered the context. Blender, a free and open source 3D modeling software, was used to rotate and translate the left boulder recorded in 3D by following the clear indications of the geological analyses which studied the fracture lines of the rocks, and that highlighted the rotations that the fallen boulder had made. Through the correct placement of the boulder it was then possible to verify the continuity of the fracture lines between the two parts of the outcrop. The left boulder was found to be compatible in the form of its fracture lines and in the inclination of its geological layers with the right part of the outcrop (Figure 8).

The shape of the outcrop after the reconstruction of its original form resembled more a rock shelter than a mining entrance. This new interpretation is strengthened by the discovery of prepared ground surfaces during the excavation. Therefore, calculations performed on the virtual reconstruction model were intended to verify whether the amount of space covered by the shelter could be considered large enough for enabling occupation of the area during the life of the main edifice of the Canonica. The 3D model of the reconstructed shelter was then used to obtain volumetric and geometric measurements of the area effectively covered by the shelter. These calculations were made using proxy solids and planes, because Blender allows only positive areas and volumes to be calculated. In particular, the '3D print toolbox' add-on and its volumetric calculation tool were used for the purpose (Figure 9).

The results of this calculation were that the roof covered an area of 21 m^2, the volume of the room was 89 m^3 and the average height of the roof of was 4.2 m.

As a final operation, the 3D model recorded with Image-based 3D modeling was integrated in its missing part inside Blender using the techniques of the 3D modeling, in order to obtain a graphic representation of the original form of the rocky shelter. In accordance to the principles of the virtual reconstruction for Cultural Heritage (Beacham *et al.*, 2006), a transparency filter was used to differentiate the integrated part from the recorded model.

This reconstruction was made because it is the authors' belief that such means of communication are very powerful in visually conveying the information and in helping other researchers and the public to visualize the original context (Figure 10).

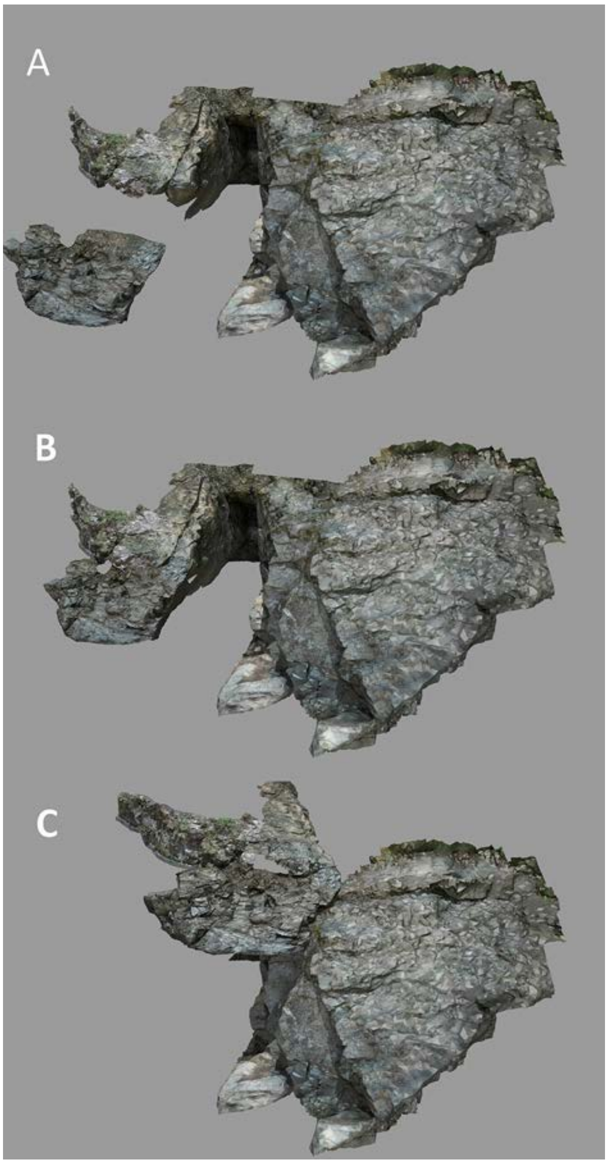

Figure 8. The virtual reconstruction process: A — 3D model of the outcrop. B — The two pieces of the left side boulder are assembled according to the indications of the geological analyses. C — Translation and rotation of the recomposed left boulder onto the right rock, to recreate the original morphology of the context.

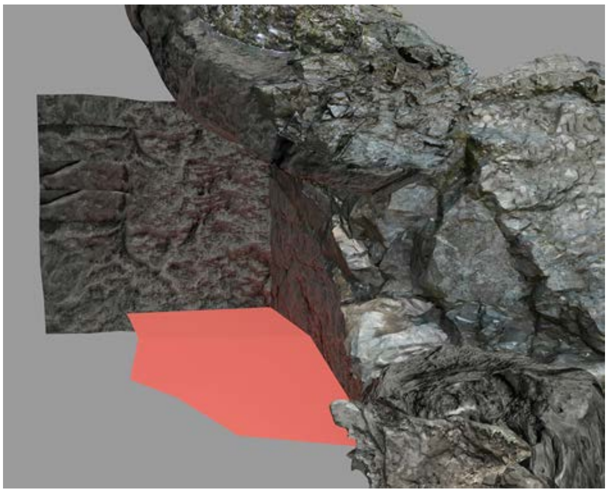

Figure 9. In red is marked the proxy plane used to calculate the area of the covered floor inside the shelter.

Figure 10. The final 3D reconstruction of the shelter as it was during the middle ages. In the first image a transparency filter was applied to differentiate the integrated and reconstructed parts of the context from the recorded ones. In the second image, the filter was removed for a greater visual impact.

Second case study: Allumiere di Monteleo

The archaeological site and the 'Building F'

The archaeological site of "Allumiere di Monteleo" is located in the southern part of Tuscany, in the territory of Colline Metallifere near the town of Monterotondo Marittimo, not far from the site of Canonica di San Niccolò (Figure 11). These hills have been for centuries the object of extensive mining activities, and in Monteleo, during the middle ages, the mineral alunite was turned and transformed into alum. Alum is a salt of aluminium and potassium [$(KAl(SO_4)_2 \cdot 12H_2O$] that has been widely used in the textile manufacturing, in the treatment of coins and in other various uses (Dallai and Poggi, 2012).

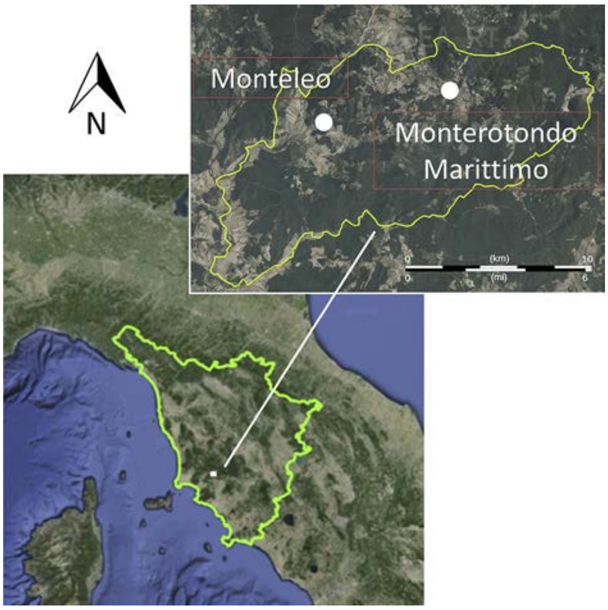

Figure 11. Monterotondo Marittimo and its territory.

Figure 12. The archaeological deposit of the 'Building F' at the beginning of the campaign.

In Monteleo the productive structures were employed discontinuously for over three centuries (15th–18th) and the signs of the intensive use are clearly visible either in the restorations of the walls of the structures, or in the collapses recorded during excavation activities, conducted by the University of Siena since 2008. One of the side purposes of the archaeological investigation was then to determine the connection between the walls and their collapse in order to estimate with higher accuracy the quantity of the alum production, and to reconstruct the volumes of the missing parts of the numerous kilns found in the site area. Volume calculations performed on 3D models were then considered the most accurate means to obtain this volumetric information.

In 2015, the remains of an isolated productive plant were located ('Building F'). This context was chosen as an ideal case study due to the fact that it was isolated from the other areas under investigation, submerged by the collapse of its own walls and appeared to be untouched by later spoliations (Figure 12). These parameters were considered fundamental to drastically reduce the potential interference in the test results.

Even though this well-preserved context was partially removed by a mechanical excavator during the openings days of the archaeological campaign, before the structure had been identified, its original extension can be reconstructed from the points measured during a survey campaign with total station, performed few days in advance. It was decided to record in 3D the entire stratigraphy of the deposit around the building, and to use the models to calculate the volume of the collapse(s). This data would be then employed inside the virtual environment to shape solids of exact size that would recreate the original height of the walls of the building itself.

The purpose of the research is therefore to verify whether the information obtained from the virtual reconstruction, along with the comparison to similar archaeological structures and iconographic sources, can be of any help in defining the typology of the building.

The issues and the recording

In order to obtain reliable volumetric data, the main issue to overcome was to establish, for each destruction layer, which was the ratio between the building materials and the dirt resulting from the decay of mortar and the accumulation of organic humus. In fact, not all the total volume of the context is the result of a collapse, and subsequent modifications generally alter the deposit. Moreover, another goal was to verify if there was a constant ratio in the composition across the several destruction layers that formed the stratigraphy nearby the structure. This procedure would also allow the estimation of the volume of the building materials that formed the missing deposit which was removed by the excavator. By applying the value of the ratio calculated on the contexts still in place to the volume of the missing deposit documented through the total station survey campaign, it would be possible to obtain the volume of the collapsed building materials even for that portion of the structure.

Therefore, a three-step process was followed in-field:

1. A 3D recording of every context which resulted from the collapse of the walls of the building, as excavated during the ongoing excavation activities.

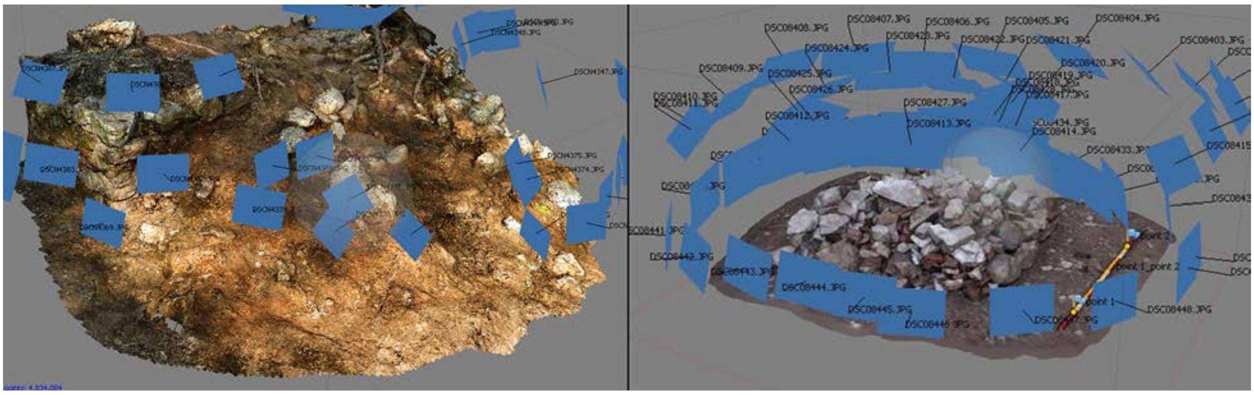

Figure 13. 3D recording and elaboration process on contexts and stacks. On the left side, the 3D model of US 3506 with the reconstructed positions of the cameras. On the right side, the 3D model of the relative stack of building materials, with the metric bar used for scale.

2. A collection of the building materials found inside each context and the creation of a stack with said building materials.
3. A 3D recording of each stack
4. Volume calculation of the contexts and the stacks to obtain the ratio

In taking the pictures for the 3D elaboration process, a Sony Alpha 6000 Mirrorless camera with a 24Mpx 23.6 mm sensor and a 16–50 mm lens, was used. For each context, an average of 30 photos were taken, as their simple morphology did not require any special precautions. However, for the stacks, a more accurate planning was required due to the complex shapes. By moving the camera around the materials, a picture was taken approximately every 20 degrees at three different heights, collecting an average of 50 pictures per stack. As per the other case study, the pictures were imported into Photoscan and processed to obtain 3D models, following the procedure explained previously in this article. The models of the contexts were then scaled and referenced in the local coordinates system used in the excavation through markers' positions measured with a total station, whereas the models of the stacks were just scaled according to a simple metric bar used as a reference (Figure 13).

Volume calculations

In approaching volume calculations we must face the fact that in these situations Image-based 3D modeling techniques can record only open surfaces, while the volume calculation requires a closed surface object. Within the excavation activity this condition can not be overcome: when documenting the contexts it is necessary to identify discontinuities between the components which represent the limits between separate consistent actions that have modified the physical space (Barcelò, 2000). An archaeological context, identified from its top surface, ends where the one below begins. According to this model, the volume of the context is enclosed by the top surface of the context itself and by the top surface of the context below. If the 3D documentation has been carried out with accuracy, the space that intercourses the edges of two surfaces can be considered null, thereby creating a closed space.

In order to calculate the volume of the contexts, ArcGIS software from ESRI was used to relate the surfaces from each context and to perform spatial analysis among the totality of the dataset. Due to the accurate topographic referentiation, the 3D models of the contexts were imported in the software keeping the spatial relationships unaffected among each other. The 'surface difference' tool, part of the geoprocessing 3D Analyst extension, has then enabled the calculation of the volumetric difference between two surface models, returning the volumes of each context (Figure 14).

However, in the case of the stacks, a different workflow was followed. Inside the 3D modeling software Blender, the modifier 'Boolean, intersect' was applied to the 3D models of the stacks with a cube as the intersecting object. This was done to close the mesh of the stack at the bottom side, recreating in the virtual environment the ground surface where the materials were placed and, more technically, creating a manifold mesh, which means a mesh describing an object that could exist in the real world. For the volume calculations, the add-on '3D print toolbox' was used, which allows the automatic extraction of the geometric properties of the objects.

By dividing the data, it was found out a constant ratio between the volumes of the context and the volume of the stacks (Table 1). At the moment only two contexts out of four are analysed: the excavation and the research are still in progress, but we feel confident that

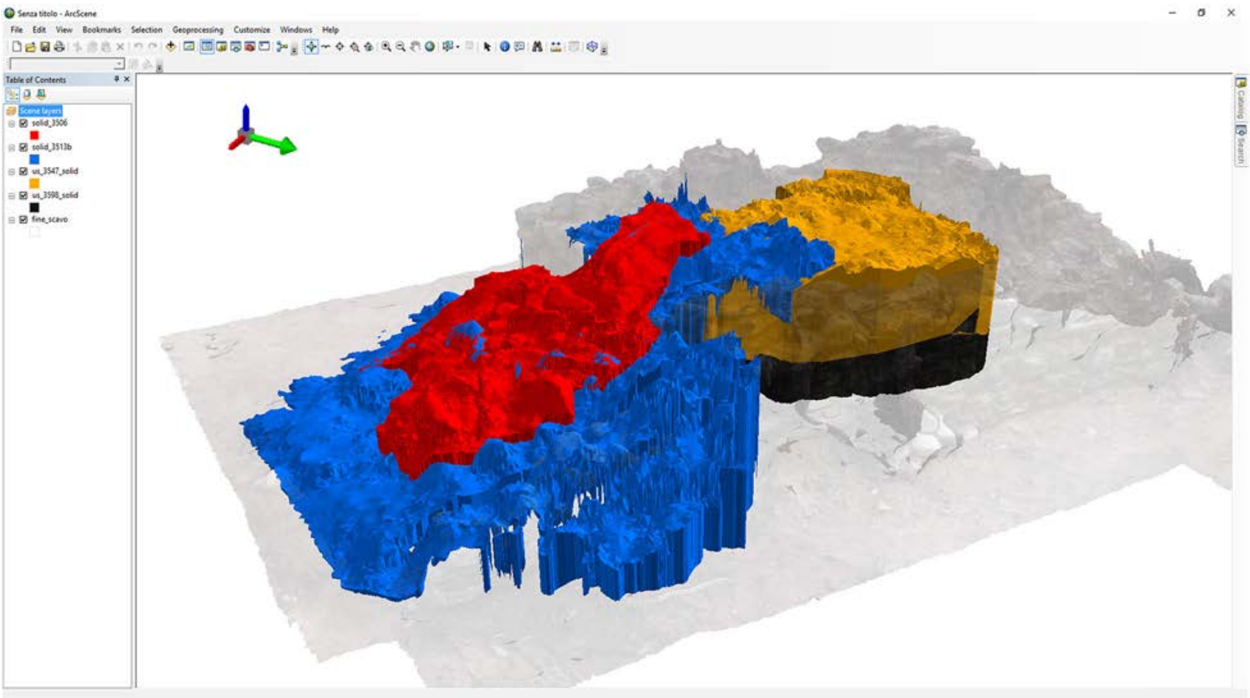

Figure 14. Volume calculation of the contexts inside ArcGIS software.

Context	Context volume	Stack volume	Ratio
US 3506	0.495 m^3	0.249 m^3	51.9%
US 3513	1.864 m^3	0.931 m^3	49.9%
US 3547		0.173 m^3	
US 3598		0.184 m^3	

Table 1.

the resulted ratio of about 50% was consistent and valid as a tool to proceed in our study. Ergo it is possible to assume with a degree of certainty that the northern deposit, the one which was removed, was affected by the same proportions between building materials and dirt because of the same condition of deposition. Of the said deposit, as already stated before, there was photographic evidence and the survey campaign made with a total station that aided in the reconstruction of its general size and shape.

Using these data and the 3D model of the remains of the building, recorded at the end of the archaeological excavation season, the missing deposit was recreated in the virtual environment of Blender in a fairly geometric shape. From a deposit volume of 3.196 m^3, the ratio of 50% was applied and the resulted volume of the building materials was estimated in about 1.598 m^3.

These volumetric data were used to create solids that were then positioned on top of the walls of the building, in the place where it was reasonable to presume the materials had fallen from, in accordance with the results of the excavation. The bases of these solids were made to copy the morphology of the standing part of the walls and the height was adjusted in order to obtain the exact value that corresponds to the volume. The northern deposit, the most consistent in terms of volumetric space, had a final height of 1.17 m, setting the total height of the building from the floor to 2.16 m (Figure 15).

During the excavation, some features found in the remaining parts of the walls seemed to characterize this building as a furnace. Due to the lack of waste pottery production ceramics but the presence of some burned bricks around the structure, it was interpreted as a brick furnace and dated to the 15th–16th century thanks to some pottery fragments.

Some comparisons for this structure can be found in another coeval excavation in San Giovanni in Persiceto, near the city of Bologna, where three similar buildings were excavated and interpreted as brick furnaces, due to notable layers of ashes in the corners inside the chamber (Gelichi and Curina, 1993). Another reference is an Italian author of the 16th century called Cipriano Piccolpasso, who wrote a comprehensive work named *Li tre libri dell'arte del vasaio* (The Three Books of the Potter's Art). In his books, he describes the common typology of furnace in use in the first half of the 16th century, giving the measures of the chamber which correspond to those of 'Building F' and specifically

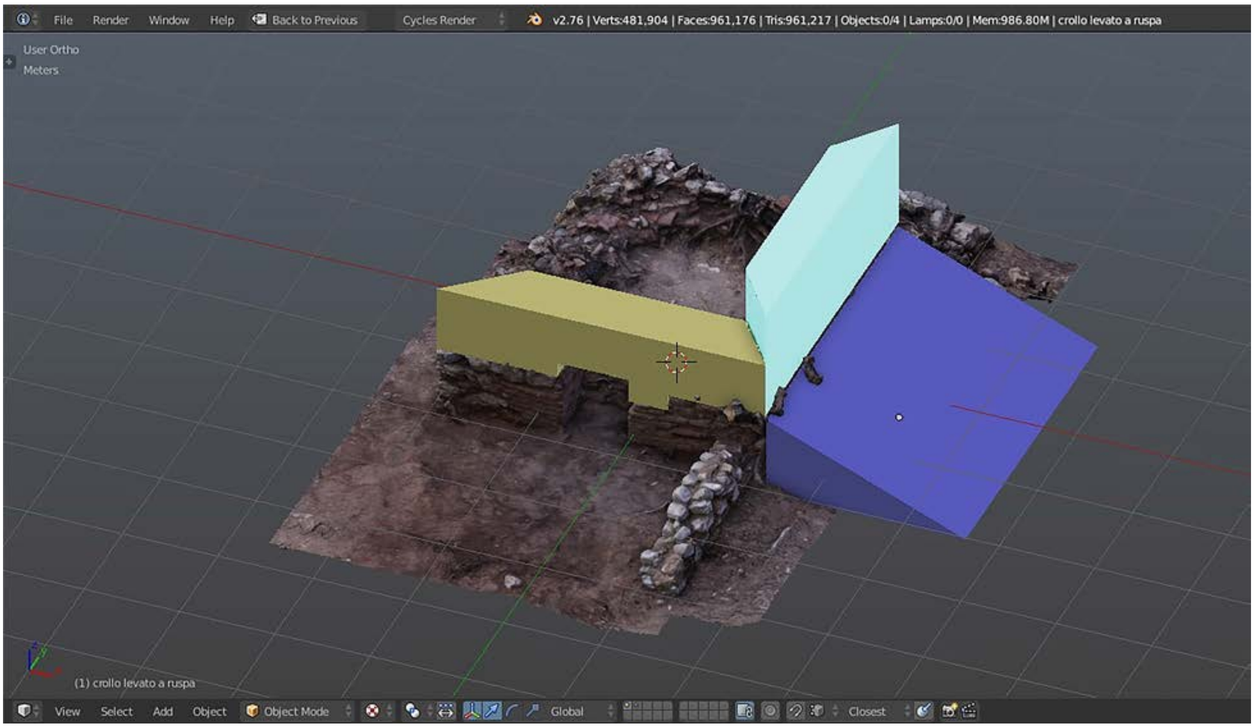

Figure 15. 3D model of the building with the solids that represent the reconstructed volumes: on the left is the solid with the volumes of building materials calculated from US3506 and US3513. On the right is the shape of the reconstructed northern deposit according to the survey measurements. The solid in the middle is shaped according to the volume of the building materials calculated from the total volume of northern deposit.

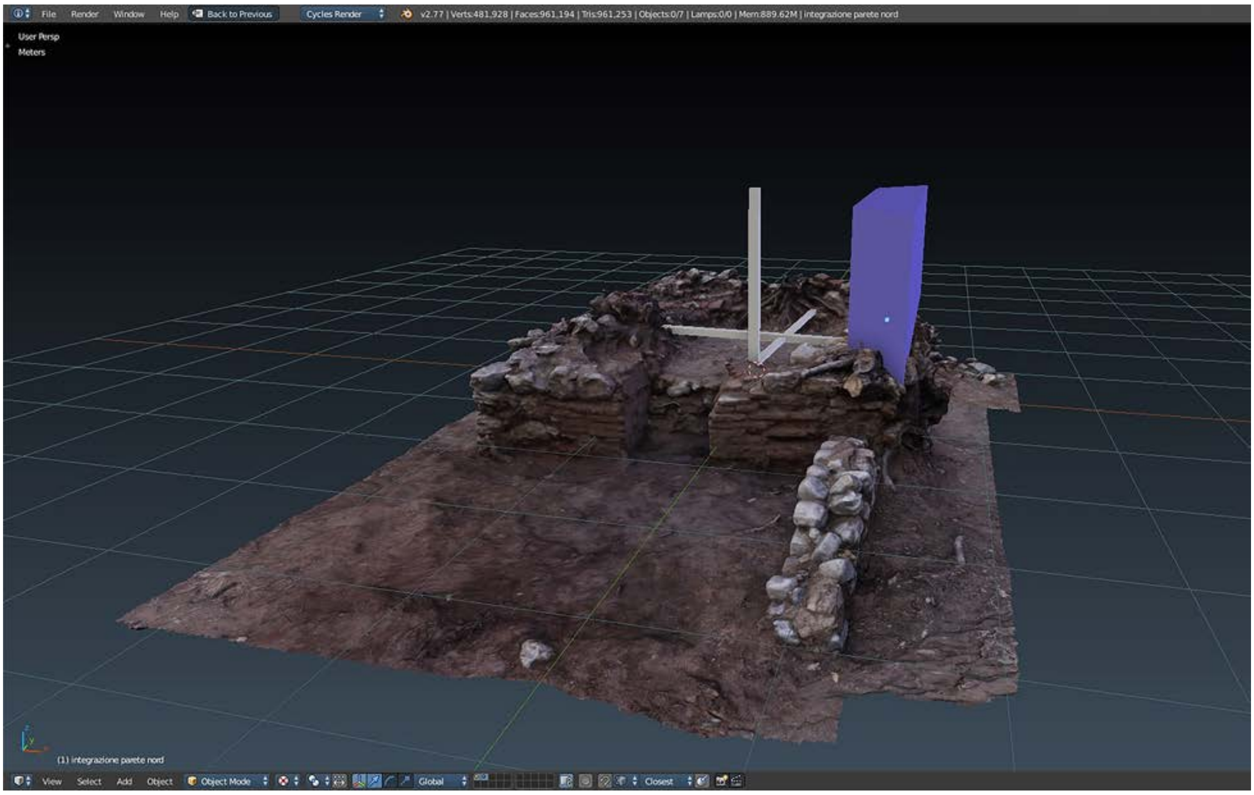

Figure 16. The two solids parallel to the ground inside the structure are the proxy solids used to measure the building. The measures are 2.348 m for the width and 2.123 m for the length. The slim solid perpendicular to the ground is the length rotated to be the proxy for the height (Piccolpasso stated that the furnace is high as it is long). As we can see, it is pretty similar to the reconstructed height given by the volume calculation for the northern deposit (the big solid to the right).

those of the reconstructed height (Piccolpasso, II, 92–95).

Piccolpasso wrote that the commonly used furnace is 5 *piedi* wide and 6 *piedi* long and tall. Taken as conversion rate 1 *piede* equals 35 cm, the ideal furnace of Piccolpasso is 1.70 m wide and 2.10 m long and tall, very similar to our reconstructed building that is 2.34 m wide, 2.12 m long and 2.16 m high (Figure 16).

The final outcome of this volumetric analyses and computations was, therefore, the strengthening of the validity of an interpretation hypothesis. It was possible to obtain the original height of the building, a type of data otherwise impossible to retrieve with the traditional approach to the recording of an archaeological context. This has been possible with little added effort during the archaeological campaign, due to the fast recording process using the Image-based 3D modeling technique.

Conclusions

It is the authors' belief that a systematic application of the proposed methodology on every archaeological context is accessible with a limited effort and it is of great benefit for the research process.

The 3D recording does not require expensive and dedicated equipment apart from the software license: reflex cameras and computers able to handle this type of calculations are generally widespread on excavations and the use of a total station, albeit being convenient for scaling and referencing the 3D models, is not necessary.

In the second case study proposed, some compromises were taken to record the stacks of building materials in compatibility with the timings and the need of the archaeological excavation. As a preliminary analysis, it was at first calculated that the difference in volumes between a disorganized stack and a more organized shape of the same stack, made by the careful placement of the materials, was of 2%. This value was taken into account for the test, but in the event of a systematic application of the methodology could be considered of insufficient significance compared to the time spent in making organized stacks. The article has shown how the combined use of 3D recording and 3D modelling can provide additional data and information for the archaeological interpretation, hardly achievable by other means of investigation.

The systematic application of this type of analysis could extrapolate additional information and data not explored in this research, in which the authors tried to present the possibilities and the potential of using 3D models not only for the documentation of archaeological evidences, but as proper tools for enhancing the archaeological interpretation.

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Mieko Matsumoto and Espen Uleberg (eds) 2018. *CAA2016: Oceans of Data*
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
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3D Spatial Analysis: the Road Ahead

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Abstract
Archaeology, like several other disciplines studying the physical landscape, is inherently about three-dimensional data; that is, about physical objects and volumes and their associated properties. Yet our records of this 3D reality have traditionally perforce been reduced to two dimensions, restricting the subsequent analysis to 2D, or at most 2.5D, as well. GIS have been the tool typically used to manage and analyse these 2D/2.5D spatial data sets since the early 1990s. Within the last decade, technological developments in data capture (such as laser scanning and image based modelling) have begun to generate large quantities of 3D data, giving rise to '3D' as the new buzzword. However, such data can be visually inspected but not spatially analysed in this form. We believe that what is lacking is a software infrastructure that can encompass both 'traditional' 2D and 'new' 3D archaeological data in the same 3D environment, and can allow for analysis in three dimensions. We propose here to construct such an infrastructure from pre-existing FOSS4G components, and to create a number of additional bespoke query and report functions in order to achieve the functionality required by archaeological researchers.

Keywords: archaeology, volumes, 3D GIS, spatial analysis, FOSS4G

Introduction

Geographical Information Systems (GIS) for the management and analysis of 2D geodata have been part of the archaeologist's toolkit for nearly three decades now. Like 2D in the 1990s, '3D' has become a hot topic in Archaeology in recent years. Figure 1 illustrates this trend through the manual categorisation of paper titles published in the proceedings of the Computer Applications and Quantitative Methods in Archaeology (CAA) conference. Within this upwards trend it is the visualization of data which is dominant; the analytical element is only rarely present. New technologies aimed at data collection and visualisation — terrestrial laser scanning, desktop digital photogrammetry, and 3D printing — have been rapidly taken up by archaeologists for documenting and visualizing objects, monuments, excavation trenches and whole landscapes (Remondino and Campana, 2014; de Kleijn *et al.*, 2015; Landeschi *et al.*, 2016). However, as noted in a recent paper (van Leusen and van Gessel, 2016), the vast majority of this work actually involves '2.5D' visualization rather than 3D spatial analysis. Only recently have archaeological researchers become concerned with true (volumetric) spatial representation and analysis of their data, as derived by techniques such as coring, archaeogeophysics, excavation, and seismics from intra-site to landscape-scale contexts.

This paper aims to highlight this biasing of data visualisation against data analysis and promote a potential e-infrastructure which could create an affordable 3D GIS management and analysis functionality for archaeological researchers. The crucial element in this functionality is the ability to ask questions about the content and topological relationships of three-dimensional entities. Although much 3D GIS theorising already happened in the mid-1990s (see amongst others Breunig *et al.*, 1995; van Oosterom *et al.*, 1994; Sides and Hack, 1995), current industry-standard GIS such as ESRI ArcGIS do not yet come sufficiently close to offering such volumetric recording and analysis functionality, as shown by Losier *et al.* (2007) and Katsiaris *et al.* (2008). Nor can we have recourse to current WebGL softwares, whose goal is purely to visualize point clouds and surfaces online.

What is '3D' GIS, and why do we need it?

It is easier to describe in general terms what a 3D GIS must be able to do than to describe what *we* want to do with it: it simply performs the 3D analogue to our current 2D GIS, on 3D simplexes (points, surfaces, volumes). Current vector GIS have 3D (x, y, z) points, and lines and surfaces based on such points. However, none of these can currently be part of a true 3D volumetric object because current GIS cannot yet infer the presence of volumes on the basis of topological relationships between points, lines and surfaces.

The term '2.5D' has been coined to capture precisely this distinction between true (volumetric) 3D and its

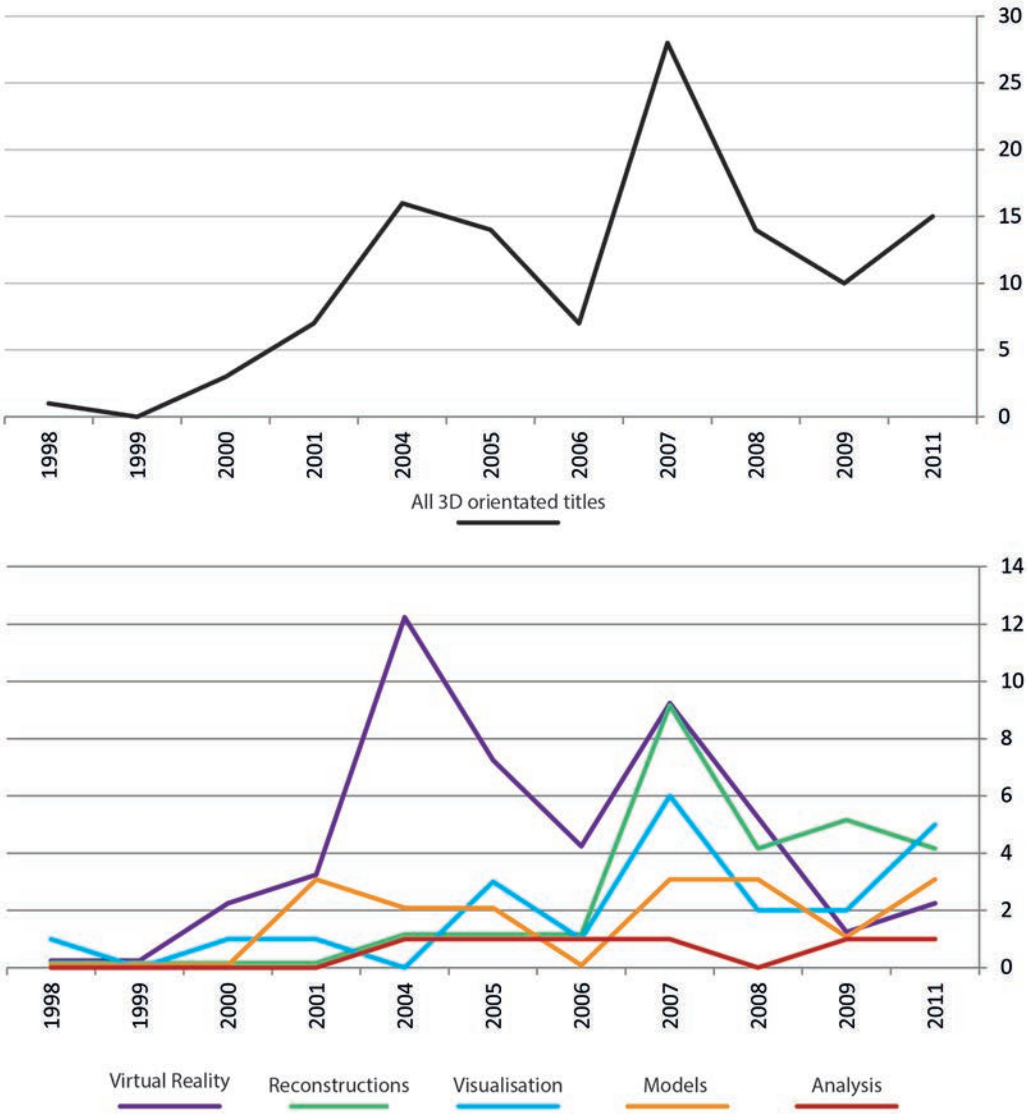

Figure 1. Frequency of the term '3D' in article titles in CAA proceedings since the last survey in 1997. Top: all titles. Bottom: subdivision by theme.

non-topological counterparts, but this distinction has now become blurred because researchers have applied the 3D label interchangeably with 2.5D. Rather than trying to reverse what has by now become an established habit, we propose to introduce three new terms (see figure 2):

- p3D: for a point dataset or point cloud with associated x, y, z data.
- s3D: for a surface representing changes in x, y, z over an object or landscape.
- v3D: for an object with a volumetric dimension.

A 3D GIS must be able to store and process these geographical simplexes in some form of vector format and, in the cases of volumes, also in a voxel format. As in its 2D equivalent, a 3D GIS must also be able to generate, store and process information about the spatial relationships between these simplexes and more complex groupings that can be constructed out of them. As in its 2D equivalent, a 3D GIS must be able to 'hand over' to other software for certain specialised tasks, such as visualisation and statistical analysis.

To highlight how a 3D GIS could be of use, we present a few potential cases from both research and heritage management perspectives.

Archaeological prospection

It is often the case in cultural resource management that the archaeological record is treated a set of *areas* of archaeological importance, whereas the archaeological record is volumetric. When building

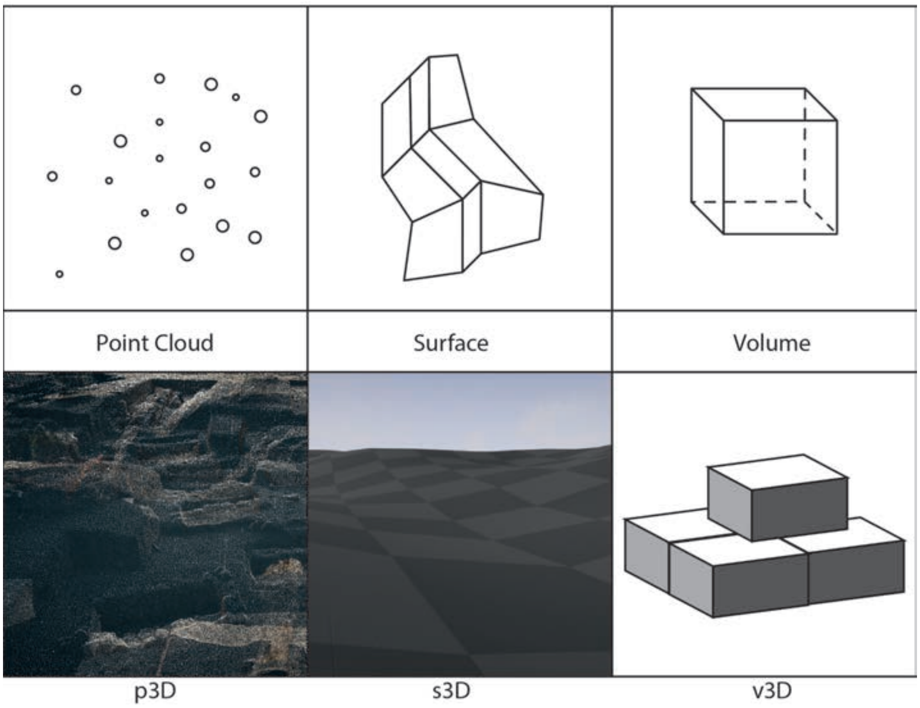

Figure 2. Diagram illustrating the distinction between 2.5D and 3D data models.

developments are proposed the archaeological assessment is commonly based on the building's footprint and its area of potential impact; the depth and volume of the archaeological resource are rarely taken into consideration. These parameters are very important as the volumetric quantification of the archaeological deposits could impact upon the financing of the archaeological mitigation. The impact on the archaeological resource in terms of depth of the building's footprint may be insufficient to warrant archaeological works. An example of this is illustrated in figure 3. Moreover, recording the absolute height (z-value) and depth of archaeological finds and features is essential for understanding in detail why some are well preserved, and others are almost destroyed by natural and anthropogenic postdepositional processes. Similarly, having a landscape-scale 3D model of the geology and soils promotes the correct assessment of potential site locations: which subsurface features tend to be favourable to both past uses and post depositional preservation? A project 'Knowledge Map 3: Expectations in Layers', currently underway at the Dutch State Service, presents the modelled depths of subsurface features such as river dunes and cover sand ridges.

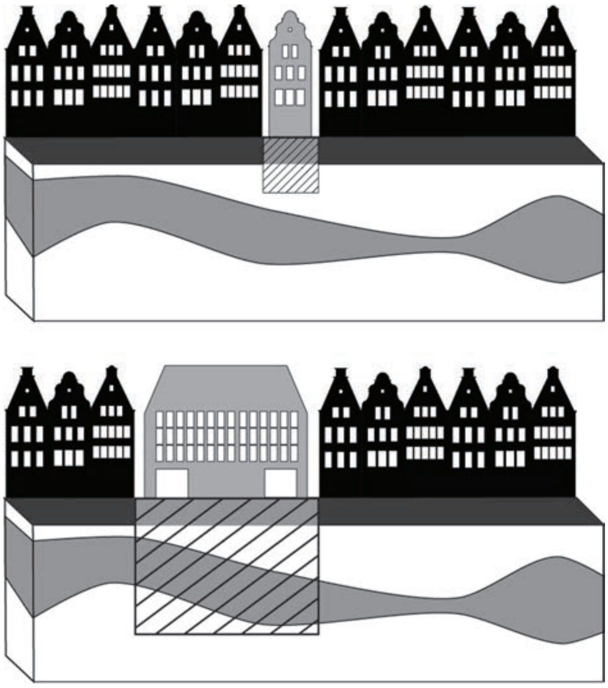

Figure 3. The degree of impact on an archaeological resource (grey) depends on depth of development: a proposed development with a shallow footprint (top), and one with a deep footprint (bottom).

Heritage management

The management and monitoring of heritage assets presents the archaeologist with complex 3D objects and relationships. A system is needed that can accurately represent and help to monitor the condition of heritage assets for their long-term preservation. 3D querying of two 3D models of a site by intersection would help to identify the movement of built structures and help to identify objects or volumes at risk (see for recent attempts Campanaro *et al.*, 2015; Landeschi *et al.*, 2015).

Perception of the environment

An 'archaeology of the senses' has been most prominent in visual studies, particularly the work concerning cumulative viewshed analysis and the generation of total viewsheds as well as perception (Wheatley, 1995; Llobera *et al.*, 2007; Frieman and Gillings, 2007). Higuchi distances are used to model the effects of distance on visual perception, whilst atmospheric influences have been explored to a lesser extent (cf. Wheatley and Gillings, 2000). A system which could apply visual impedance through atmospheric modelling would add much to this debate and move us beyond the 2D quantification of 3D space (cf. Paliou and Wheatley, 2007; Landeschi *et al.*, 2016). The modelling of the atmosphere could also enhance our understanding of the role of soundscapes and past human perception (cf. Mlekuz, 2004) through changes in atmospheric conditions (fog, mist, wind direction). A system which could include atmospheric modelling would be able to incorporate the viewshed and soundscape together as illustrated in Figure 4; volumetric intersection queries could then identify volumes of view and sound, invisibility and silence. Phenomenological enquiry combined with digital methods has already moved perception studies forward through the incorporation of digital models and sensual stimulants (see Eve, 2012).

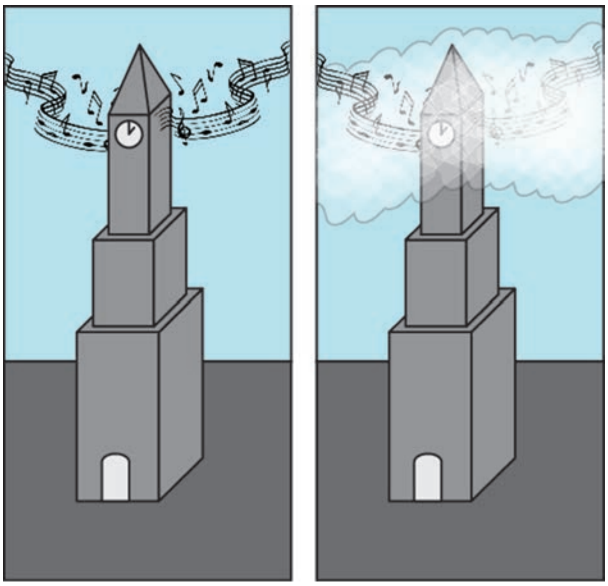

Figure 4. Characteristics of air volumes affect viewsheds and soundscapes but are not modelled in 2D GIS. In this example, a church clock tower, both sight and sounds are affected by mist and low cloud.

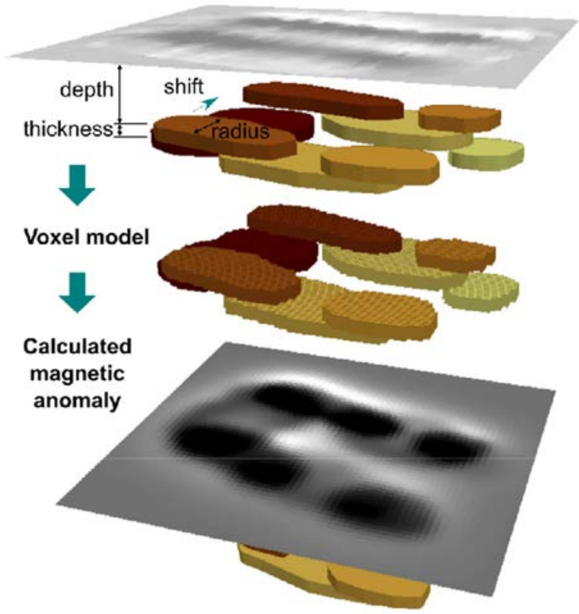

Figure 5. Geophysical instruments measure 3D characteristics of the soils and archaeological features, which are then visualized and analysed in 2D. However, v3D models are needed to understand how a 2D 'anomaly' is generated by the use of a specific instrument over a 3D volume, as in this example of an inverse model (bottom: after Schmidt *et al.*, 2015).

Geophysical prospection and interpretation

Voxel modelling of archaeological deposits from geophysical information should also allow archaeologists to test hypotheses such as shown in Figure 5, where a hypothetical voxel-based model of archaeological features has been used to generate an expected geomagnetic response, which can then be compared to actual field readings.

These few examples serve to highlight the need for a 3D-query enabled GIS environment.

The state of play

Current GIS software packages are limited in this regard: the proprietary market leader ESRI's ArcGIS is 2D, ArcScene was an attempt to move into 2.5D representations of the 2D data, most recently their release of CityEngine has moved closer to a 3D environment, yet it should still be considered 2.5D as it represents surfaces, and not volumes. Furthermore, it is not a GIS environment, it is a geodesign modelling environment more suited for urban planners to visualize potential developments and to visually assess any impact such construction may have on the surrounding urban environment. The open source movement has developed Free Open Source Software

Figure 6. Current GIS '3D' capabilities are illustrated by GRASS GIS (2014) landscape visualisation tools like r.out.pov (left) and ESRI CityEngine (2013) (right).

for Geospatial data (FOSS4G); within this GRASS GIS has made the biggest strides in 3D representation. Building upon its strong raster heritage it can create and manipulate voxel datasets — true v3D entities — but it must then export this data to visualization packages such as ParaView. QGIS, like ArcGIS, is far more suited to vector data, but it cannot manipulate 3D datasets. Web browser technology is increasingly competing with desktop solutions, the rise of the Web Graphics Library (WebGL) allowing for the rendering of objects in any HTML5 compatible web browser through the use of the JavaScript API. The rise of WebGL has led to the sharing of online p3D point clouds,[1] a 2.5D approach that has been applied, for example, to the 'Mapping the Via Appia' project (de Kleijn *et al*., 2015). 3DHOP[2] (Potenziani *et al.,* 2015) is the next development; this moves on from the p3D approach and creates an s3D surface visualisation. An online volumetric WebGL application — the next logical evolution of WebGL — has yet to present itself. None of these technologies can be regarded as truly three-dimensional unless they include volumetric data. As it stands, no 3D GIS solution has therefore presented itself from either the GIS market leader or from the Open Source movement.

A FOSS4G infrastructure for 3D GIS

The approach we propose here is to build up the requisite e-infrastructure for the management and analysis of 3D data, mostly from existing FOSS4G components, whilst ensuring that these modules all properly 'talk to each other' and that any significant shortcomings in the functionality of the system as a whole are dealt with. Rather than attempting to build an 'ideal' system from scratch, we take the pragmatic view that what potential end users need right now is to be convinced that the gains outweigh the investment needed. Hence our system need only allow for the development of realistic 'showcase' studies.

The system will need to deal with key technological challenges related to the handling of 3D data in both vector and voxel formats (Lieberwirth, 2008; Penninga and van Oosterom, 2008, pp. 751–752; Merlo, 2010). As shown in Figure 7, we can use existing FOSS4G software to build an infrastructure for archaeological 3D data analysis, with a PostgreSQL database at its core. A series of linked modules will require creating or updating to allow archaeologists to create, manage, and query their domain-specific 3D data sets; e-science expertise in general programming, database programming, and GUI programming will be needed to build this integrated system.

Data structure and storage: vector data

Firstly, and most important, is the data storage. An Object Orientated approach is required; a PostgreSQL database with the PostGIS extension creates an Object Orientated Spatial Data Base. This has some key advantages over the traditional Relational Spatial Database. The relational database stores data over many tables, it is organised in relation to the attributes

[1] see http://ahn2.pointclouds.nl/ for an example
[2] http://3dhop.net/

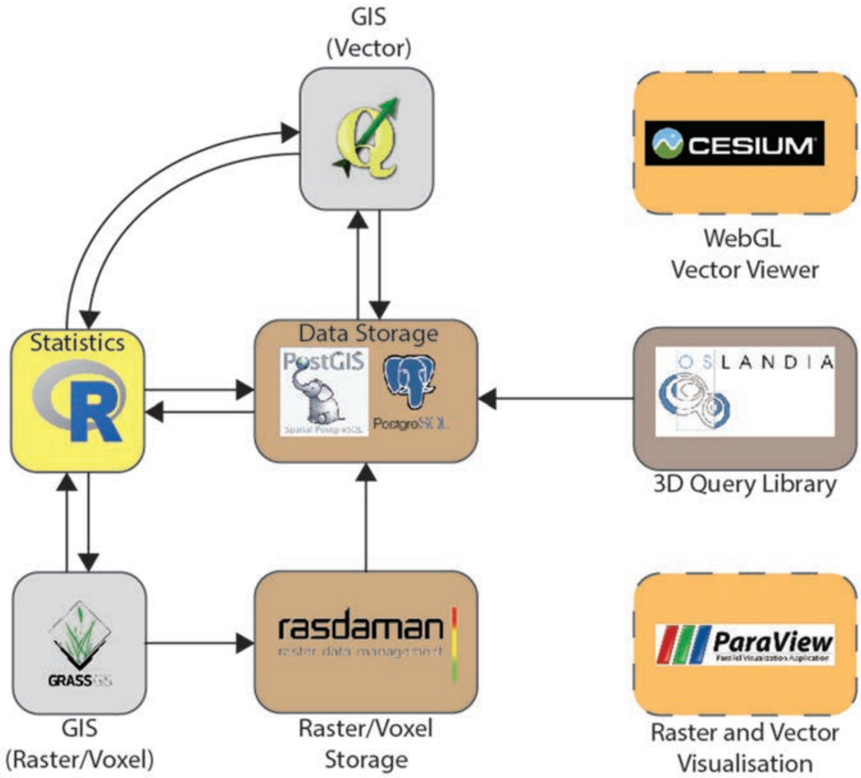

Figure 7. Proposal for an object-oriented 3D e-infrastructure framework composed of FOSS4G modules.

whereas in an object orientated database each object has its own table. This means a single object can be duplicated by copying a single table rather than inserting new rows into numerous related tables. It also allows for simple spatial querying where complex queries would be needed in the relational system. The object orientated database can also store relationships between objects, for instance: a brick can be part of a wall.

Querying

Once stored the 3D data needs to be able to be queried either by attributes or spatially. A new library for 3D querying was produced by Oslandia in 2013, adding 3D queries to the PostgreSQL framework. These include:

- ST_3DIntersection
- ST_Tesselate (3D volume to triangulation)
- ST_3DArea
- ST_Extrude
- ST_StraightSkeleton (creates a vector skeleton of an object)
- ST_3DIntersects
- ST_Distance

ST_3DIntersects is a query function to determine if one object is intersecting with another, while the ST_3DIntersection function allows for the division of volumetric objects into two new objects. The letter is particularly useful if an object (like a wall) needs to be divided into smaller elements (such as bricks). More functionality is currently in development (such as 3D Union Relate, Simplify) as well as enabling WebGL visualisation. Meanwhile visualisation of these results is possible directly using Horao to link to the QGIS 3D viewer.[3]

Interoperability

Due to its open nature, FOSS4G allows for interoperability between various software packages. Figure 7 illustrates the potential for such a system: while the spatial database manages and stores the data, other packages can access the data without the need for exporting between programs. As stated above, QGIS can be used for viewing the data and for assessing the result of queries. A mature system should also allow for statistical analysis, which can be provided by the statistics package R as it can connect to both the spatial database and to QGIS.

Voxel support

As 3D raster support is limited in these packages, GRASS GIS can be used to create and manipulate voxel data

[3] see http://www.oslandia.com for further details

using built-in tools and 3D map algebra (see its 'r3' functions[4], e.g. r3.mapcalc). The data can also be stored in a PostgreSQL database via a raster data management library such as Rasdaman.[5] GRASS GIS can invoke R internally, can be used within QGIS, and can connect to spatial databases. As matters now stand, we foresee the development of tools and methods to:

- Convert between vector and voxel datasets
- Extend the 3D query functions of the Oslandia libraries
- Update the r.vol.dem module from GRASS GIS 6.4 to 7.1
- Implement basic statistical analysis by R integration
- Implement export functions to visualization software such as ParaView or Cesium

Conclusion: how to bring this about?

The analytical requirements of Archaeology are not substantially different from those of other disciplines involved in the study of physical space, such as geology, meteorology, hydrology, and pedology. Therefore lateral mobility of 3D GIS technologies is not just possible, but very probable and essential. The proposed software infrastructure will potentially impact a large international research community with needs for volumetric 3D modelling. The software modules to be linked for this project are already part of the FOSS4G initiative, and the e-infrastructure as a whole should be ported to this worldwide community to ensure its sustainability, dissemination, and continued management.

Collaborations can already be anticipated in the Netherlands through the TNO GeoTOP program for modelling the top 30–50 meters of the Dutch subsurface, and the '3D Doorbraak' initiative,[6] and the international and national chapters of the Computer Applications and Quantitative Methods in Archaeology (CAA) foundation. Steps have been taken to start Special Interest Groups at the latter two, and further collaborations will be forged through the creation and use of an international test panel consisting of e-scientists and domain specialists. Engaging with the FOSS4G community and forging cross-disciplinary alliances will take time.

In the meantime it is essential that new funding redresses the new imbalance between the 3D visualisation of 'pretty models' and the analytical investigation of 3D space. Such an infrastructure will present many new opportunities: the incorporation of properties to allow for atmospheric variation for vision and sound studies; the effective management of heritage assets; cross validation of archaeological features and geophysical anomalies; the potential to translate topological relationships of features and deposits into a 'Harris Matrix' (1979) graphical representation; structured querying of 3D objects; and bringing all this functionality into a single user environment.

Whilst the technology discussed here is a crucial element to 3D data querying and documentation, we archaeologists will also need to rediscover how to document and manage data in three dimensions when our whole training has prepared us for reducing 3D space to two dimensions.

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[4] See GRASS Development Team (2008–2012) for full list.
[5] http://www.rasdaman.org
[6] http://www.geonovum.nl/onderwerpen/3d-doorbraak

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Complex Systems Simulation

Mieko Matsumoto and Espen Uleberg (eds) 2018. *CAA2016: Oceans of Data*
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
Oxford: Archaeopress

Weaving the Common Threads of Simulation and Formation Studies in Archaeology

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Abstract
Computer simulation is a tool increasingly used by archaeologists to build theories about past human activity; however, simulation has had a limited role theorising about the relationship between past behaviours and the formation of observed patterning in the material record. This paper visits the argument for using simulation as a means of addressing the gap that exists between archaeological interpretations of past behaviours and their physical residues. It is argued that simulation is used for much the same reason that archaeologists use ethnographic or experimental studies, and that computational models can help to address some of the practical limitations of these approaches to record formation. A case study from arid Australia, examining the effects of episodic surface erosion on the visibility of the record, shows how simple, generative simulations, grounded in formational logic, can be used to compare different explanatory mechanisms and suggest tests of the archaeological record itself.

Keywords: formation, simulation, digital archaeology, Australia

Introduction

In February of the year 2000, a low pressure system moved across western New South Wales, Australia, bringing heavy rains to many parts of the region, including the Nundooka study area near Fowlers Gap Arid Zone Research Station. Archaeologists working in the area had surveyed the surface archaeology during the previous year, and returned to survey again the following winter. In their follow-up survey, they noted an abundance of vegetation that obscured many parts of the study area that were once highly visible. It was also observed that erosion in some places had winnowed away topsoils, exposing a greater abundance of smaller artefacts, while concentrated flows in other parts of the study area decreased the number of small flakes. This serendipitous co-occurrence of an archaeological survey and a large-scale fluvial event is an example of a 'natural experiment'; an opportunity to evaluate the effects of a natural process that is otherwise difficult or impossible to control (Tucker, 2009). The effects observed at Nundooka were not uniform across Fowlers Gap landscape: for example, stream action in another study area knocked out previously recorded surfaces dating back to the mid-Holocene. However, these are only two expressions of this process within a range of settings that went mostly unobserved. Additionally, the event-driven natural processes that condition the surface record in this part of the world, such as large scale flooding and aeolian sediment transport are fairly rare occurrences, and being in a position to measure their effect on the archaeological record at all is even rarer given their unpredictability. The next such opportunity would not come for another decade, after the field seasons for the project had already ceased.

Natural experiments such as these are useful for providing primary observations and generating hypotheses in systems that are otherwise difficult to experiment with. However, relying on these to understand large-scale processes would make building and testing theories about the landscape history of place like Nundooka untenable. Archaeological theory-building depends on the association of arrangements of material objects observed in the present with processes that occurred during the past to form them. But the sum of those formational processes cannot be observed, only the patterns they leave behind. Archaeologists cannot experiment directly with many suspected generative processes, because they occurred over long periods of time and involved subjects that are logistically or ethically impossible to constrain (e.g. humans, ecosystems, etc.). This is especially true of human behaviour considered beyond the ethnographic scale, where substantial variation might be expected to occur over both time and space.

To overcome the gap between observed patterns and suspected processes, many have emphasised the need for appropriate analogues (e.g. Dunnell, 1992; Gifford-Gonzalez, 1991; Gould, 1965; Johnson, 2010, p. 50; Murray and Walker, 1988; Wylie, 1985). However, faced with the expansive and temporally inconsistent nature of archaeological record, some difficult questions arise. Most immediately, what analogues exist for landscapes or regions, particularly analogues that are capable of being observed simultaneously? Furthermore, how does one find substitutes for the time it takes for long-term generative processes to operate? The processes that operate at these scales (social, ecological, formational, or otherwise) produce emergent residues, and as such cannot be simply reduced into their constituent parts, nor can it be assumed that they can be collapsed to a past snapshot comparable with an ethnographic scene. Even if it were the case that such a reconstruction was possible, the combinations of processes which came together to produce an observed pattern are but one outcome from a host of possible historical contingencies that different combinations of processes might produce (Gifford-Gonzalez, 1991; McGlade, 2014). Outside of case-specific statements, how would such an analogy inform on general theory? In this paper, it is argued that computer simulations can provide such analogues, moreover, they are a suitable means for studying of the complex entities of interest to archaeologists. These notions have been raised before, but often not in connection with the formation of the archaeological record. By highlighting similarities between the ideas behind archaeological record formation and the use of simulation for understanding the past, this paper presents them as parts of a common framework for building archaeological theory.

The common threads of formation and simulation

Connecting present day archaeological patterning to processes operating in the past has been a clear aim of archaeological research for decades (Ascher, 1961; Bailey, 1981, 1983; Binford 1981; Gifford-Gonzalez, 1991; Schiffer 1972, 1987) and consistently features in introductory descriptions of the discipline (Scarre 2013, p. 24; Renfrew and Bahn 2012, p. 11). If archaeologists aim to explain or interpret patterning in archaeological deposits with some authority, with the parallel anthropological aim of implicating some human behaviour in that explanation, then the task of the theorising archaeologist must be to develop a strong inferential link between those patterns and suspected generating processes (Murray 1999, p. 24). To study how archaeological objects come to be in their present arrangement is to study archaeological *formation*.

It is not empirically sufficient to interpret processes operating in the past solely from analysis of patterns. There are several reasons why this is the case, which tend to be subsumed under the heading of *equifinality*. First, patterns may not be intuitively recognisable as the outcome of a given process. Such a situation might arise because the pattern itself lacks a unique structural isomorphism (Cale *et al*., 1989), or the observer lacks a referent pattern for comparison. The inverse notion that the same pattern might be generated by more than one process is likewise problematic (Levin, 1992; Beven, 2002; Premo, 2010). There are numerous cases where archaeologists have developed multiple models to explain the same phenomena, but defining archaeological explanations or interpretations as equifinal is questionable because their status as such may only be fleeting. Rogers (2000) notes this in the study of faunal remains, differentiating between a mathematical definition of equifinality (*sensu* von Bertalanffy, 1949, p. 157) that declares generative mechanisms as equifinal only when they produce precisely the same outcome, and a more colloquial definition used by archaeologists in which outcomes are not the same, but only similar. If archaeological interpretations were truly equifinal, then there would be no hope of discerning between the proposed generating processes, nor much need to. Alternatively, if outcomes are only equifinal in the sense that it is *difficult to compare* generating archaeological models in terms of the available data, they might be better described as provisionally under-determined by the data at hand (Laudan and Leplin, 1991). This may be in part due to a lack of comparable data, but may also be due to a lack of appropriate mechanisms for discerning between patterns in existing data. In both of these cases, the problem of under-determination between presented alternative explanations is potentially a resolvable one.

For historical sciences, in order to associate a pattern with a presumed process acting in the past, the acceptable range of variability for outcomes of the process in question, with respect to the pattern observed in the archaeological record, must be established; in other words, its material signature. This is what Binford (1981, p. 26) refers to as ‘criteria of recognition’ for the operation of past processes, and speaks to ‘performance’ standards identified by Dunnell (1992) as fundamental for empirical studies. These cannot be observed directly, so analogous systems must be used as surrogates. This is sometimes achieved through actualistic studies under controlled conditions (e.g. Dibble and Rezek, 2009), natural experiments, or through ethnoarchaeological studies of contemporary social groups (e.g. Skibo, 2009). These kinds of observations take place in the present, so to be applied to the past the causal relationships between the analogue process and the analogue pattern must be assumed to be uniform through time and across space. In instances where such uniformitarian assumptions are warranted, archaeologists can evaluate ‘how an object interacted with its environment [in the past] with exactly the same certainty as if it were moving in front of us’ (Dunnell, 1992, p. 215).

It is fair to say that many simulating archaeologists employ computational models to overcome the barrier of being unable to observe or experiment with processes occurring in the past (Aldenderfer, 1991; Kohler, 2000; Premo, 2010), which is much the same reason that formation-oriented approaches make use of ethnographic analogy and experiments. Differences certainly exist between earlier formation approaches and more recent conceptualisations of archaeology as a model-based science, but many of these are arguably superficial when compared with the obvious similarities. Specifically, the language adopted by model-based archaeological studies is primarily experimental, viewing simulation as a 'virtual laboratory' (Kohler *et al*., 1996; *cf.* Binford, 1981, p. 29). Both simulation and formation-based approaches such as middle-range theory and behavioural archaeology have been promoted to generate a better understanding of variability in the outcomes of processes that formed the archaeological record (Aldenderfer 1991, p. 222). Premo (2007, p. 27, emphasis in original) notes this when he refers to exploratory agent-based simulation as a form of 'experimental ethnoarchaeology', and argues that:

> 'Exploratory agent-based models start with theory. They allow us to build a set of expectations that can then be evaluated with observed empirical data. As a result, they can facilitate tests (of our assumptions or of a particular hypothesis) that do not suffer from the same pernicious circularity that confounds studies that use the same set of archaeological data *both* to formulate hypotheses about archaeological formation processes *and* to test them.'

Ethnoarchaeological and actualistic studies have been historically limited by the inability to extend observation over large spatial and temporal scales, or to study social processes at higher orders of social organisation. Processes that generate discrete phenomena, like cut marks on bone, can be observed in experimental or field settings, and that knowledge of the causal relationship between pattern and process can be effectively leveraged via uniformitarian assumptions to interpret the signatures of some causal mechanisms to the exclusion of others. But understanding higher-order phenomena, such as why different frequencies of cut marks occur in different places, or why the relative frequencies of different kinds of cut marks changes over time, is not simply a matter of doing more bone modification experiments. The systems that generate these kinds of patterns may be composed of individual instances of bone modification, but are connected by relationships that may or may not be linear, or may be associated with elements that do not bear directly on the formation of modification signatures but influence other components of the broader archaeological pattern. The resultant phenomena exhibit emergent qualities that are not captured by a study of the proximal causal mechanics alone. On this matter, persisting in using middle-range analogues of lower-order phenomena to directly assess higher-order phenomena will inevitably result in more instances of equifinality (at least as understood archaeologically; see Gifford-Gonzelez, 1991).

This conundrum parallels the motivations that drive research in the field of complex systems. Among the main tenets of complex systems theory are the notions of self-organisation and emergence; in other words, that complex, higher-order structures that are identifiable, describable, and in many cases quantifiable entities unto themselves can emerge from simpler, lower-order interactions of individual system components (Anderson, 1972; Bak *et al*., 1987; Weaver, 1948, p. 539). Being properties of evolving systems, defining emergent structures necessitates the incorporation of time and space, operating at scales both synchronous with, and different from, those of their constituent parts (Levin, 1992, p. 1950; Goldstein, 1999, p. 50). These ideas correspond well with contemporary conceptualisations in archaeology of the relationships between individual agency within socio-ecological systems (McGlade, 1995; Bintliff, 2008, p. 160), facilitating the application of simulation methods in this area, but it also meshes ideas associated with archaeological formation that view the record as being perpetually in a state of becoming (e.g. Ascher, 1961; Schiffer, 1976; Binford, 1981; Bailey, 1983; Lucas, 2008; see also Pred, 1984).

There have been numerous applications of simulation in archaeological research, with the number increasing in recent years. The lion's share of these studies emphasise sociocultural evolution and human-environment interactions, with model outcomes that often reflect changes in the social entities or environments being modelled. On the other hand, few studies presented to date are focused on processes that directly influence the archaeological record. Costopoulos (2010, p. 24) argues that while they might trade in social or ecological theories, generalised archaeological simulations should be capable of including elements that bear directly on material residues. This may be true, but based on the record of published studies (see Lake, 2014, for example), this connection is not usually emphasised, and it has been argued that the promise of simulation to address questions about complex systems in the past has not translated easily to inferences regarding the formation of patterning in the material record on which archaeological inferences are made (Barton, 2014, p. 310).

Archaeological simulation is not unique in its limited engagement with formation processes. While the actual feelings of archaeologists are difficult to gauge, there is a sense that while formation is generally recognised as an essential component for making archaeological inferences, it is not given as much attention as other areas of archaeological interpretation. This sentiment is encapsulated in an informal exchange between Michael Shanks and Michael Schiffer (Rathje *et al.*, 2013, p. 35). Schiffer, when asked why formation studies had not been more enthusiastically embraced by archaeologists, responded:

> 'Although I really don't know, I can furnish one facile answer. Archaeologists do get it, but they recognize that taking into account formation processes complicates the research process, burdening us with labor- and thought-intensive activities. Many archaeologists are willing to take shortcuts because accolades flow swiftly and surely to those who craft fascinating and far-reaching inferences consistent with the latest theoretical fashions — regardless of how firmly they have been grounded in archaeological principles and archaeological evidence.'

This notion, that researchers will choose more-interesting-but-empirically-shaky research over less-interesting-but-empirically-sound research, could be read simply as cynicism, although it has been suggested that similar types of decisions in other disciplines are endemic to the contemporary academic research climate (e.g. Nosek *et al.*, 2012). It also echoes an earlier dilemma discussed in Wylie's (1985) treatment on the use of analogy in archaeology, in which the search for meaningful interpretations is contrasted with the more menial task of accounting for physical arrangements of artefacts. According to this characterisation of the dilemma, formation studies in isolation represent an intellectually sterile form of 'artifact physics' to be contrasted with a more fulfilling interpretive archaeology which is ultimately more speculative (DeBoer and Lathrap, 1979, p. 103). Rather than operating as a common interpretive framework for the study of the archaeological record, the study of formation is instead viewed a spoiler, highlighting the same disconnect between the informational content of archaeological deposits and the interpretations derived therefrom (Shott, 1998, p. 321; McGuire, 1995, p. 174; Wood and Johnson, 1978, p. 369).

In sum, simulation and formation-based approaches share common philosophical strains and goals, in particular their use of analogical reasoning, and an interest in explanation of emergent phenomena through the interaction of individual system components. However, simulation and formation concepts are rarely used in tandem, despite simulation's ability to extend explanatory models beyond a local, ethnographic scale. The following case study demonstrates one way that simulation can be effectively used to help understand the processes that form patterns in the archaeological record, and how the knowledge gained from simulating formation processes can help to differentiate between different formational mechanisms and, ultimately, interpretations of past human activity.

Simulating formation of surface archaeological deposits: an Australian case study

The case study comes from the arid region of western New South Wales, Australia, which has been occupied by humans for more than 50 thousand years. The land is predominantly low (< 250 m elevation) and flat, with most surface undulations surrounding creek catchments and ephemeral lakes in the form of low hills and dunes. The Darling River is the primary drainage for the region, which experiences extreme fluctuations in flow rate, and dry and ephemeral lakes are common features in the river's past and present overflow areas. A long-term history of erosion has exposed extensive areas of subsurface sediments and concentrations of artefacts, presenting a surface record that is highly visible and notoriously difficult to interpret (Pardoe, 2003).

Among the objects commonly found in the region are heat-retainer hearths (Figure 1), which are manifest as concentrations of fire-altered stone. Ethnographically, heat-retainer hearths were constructed by digging a shallow pit and lining it with stones. A fire was built on the stones, and then food was placed on the stones and covered with hot ashes for cooking. As sediments surrounding a hearth erode away, hearths appear as dense piles or caps of fired rock that eventually disintegrate as the baked earth holding them together is winnowed away. Sometimes, these caps protect charcoal which can be used to provide a radiometric date (Fanning *et al.*, 2009).

Radiocarbon data obtained from the Rutherfords Creek study area, about 30 kilometres east of the town of White Cliffs, shows increasing frequency of these features

Figure 1. A collection of heat-retainer hearths on an exposed surface at Rutherfords Creek.

through time. Similar patterns in large radiocarbon databases around Australia have been identified, stoking longstanding debates over the population history of the continent and the presence or absence of a definable period of socioeconomic 'intensification' during the late Holocene (Smith and Ross, 2008; Williams, 2013). Alternatively, this pattern has been suggested to instead be the result of time-dependent decay on the archaeological record (Holdaway *et al*., 2008). In addition to this trend, hearths appear to be clustered in time, interspersed with gaps where hearths are less frequent. These gaps have been shown to broadly correspond with palaeoenvironmental proxies for aridity, and have been explained as temporary periods of abandonment (Holdaway *et al*., 2010) or changes in ranging behaviour (Smith, 2013). Most of the disagreement is over whether the increasing frequency of dates is due to population growth or loss of preservation.

Outlining assumptions that should accompany the use of summed radiocarbon data as a proxy for human population history, Contreras and Meadows (2014, p. 606, emphasis in original) argue that researchers must be able to demonstrate that 'the link between production, preservation, and analysis of datable organic material and population *in that case* is sound'. Whether or not a link between these three aspects of demographic reconstruction from summed radiocarbon data has been made, and made soundly, for surface deposits in western New South Wales is debatable. For instance, while the use of data transformations to account for differential preservation in these surface deposits has been advocated in some instances (e.g. Smith, 2013), taphonomic corrections assume a decay relationship between time and age that does not incorporate the specific effects of formational processes on the condition of deposits at the time of recording (see Williams, 2012, p. 585). If this is the case, then it is necessary to understand how formation processes affect not only the preservation of these deposits through time, but also their visibility in the present, if radiometric dates obtained from surface deposits in western New South Wales are to be used in reconstructing population histories.

These two properties, preservation and visibility, are in large part controlled by the sedimentary history of the deposit, as the local rate of sedimentation determines whether a deposit is buried or exposed, and whether it is subject to surface geomorphic processes or not (Waters and Kuehn, 1996; Ward and Larcombe, 2003). Differences in the relative frequencies of erosion and deposition of sediment over time and space are likely to produce different patterning within the chronological distribution of discoverable features in surface deposits (to say nothing of subsurface features). Fanning and colleagues (2007; *sensu* Renwick, 1992) propose a model of 'episodic non-equilibrium' to describe the processes forming the surface archaeological record in western New South Wales, in which large-scale, intermittent geomorphic events relocate sediments within low relief creek valleys, with the effect of either masking or exposing archaeological materials lying on the surface. Since shallow slopes prevent overland flow from reaching velocities capable of moving larger objects (>20 mm) (Fanning and Holdaway, 2001), the result is a set of lagged artefact deposits seated on top of 'a mosaic of differently aged surfaces many of which lie adjacent to one another' (Fanning *et al.*, 2007).

A simulation was produced to explore the effects of episodic erosion and deposition on the distribution of ages in visible surface hearths (Davies *et al*., 2016). In the simulation (Figure 2), agents move randomly from point to point within a gridded space, constructing hearths at a constant rate per annual time step. If nothing else were to happen, the record would show no change through time. Hearths contain a carbon age which records the date the hearth formed in years before present. Grid cells also contain a set of sedimentary layers, each of these also containing an age, with new hearths being constructed on the surface. At a given interval (10, 50, 100, or 200 years), an event will occur with one of two outcomes; erosion or deposition. If erosion occurs, the youngest layer of sediment is removed, and any hearths situated on that surface lose their charcoal and become inaccessible for radiocarbon dating, while surfaces underneath become visible. If deposition occurs, a layer of sediment is added to the cell, and any hearths visible on the surface become hidden and thus undetectable in a surface survey. At the end of each simulation run, a sample of the hearths sitting on the surface is taken and compared to the chronology reconstructed from them. The simulation takes place between 2000 BP and present; the period of interest for the patterns discussed above. An Overview, Design Elements, and Details document describing the simulation in more detail is available as an appendix.

An initial test (Figure 3, black envelopes) showed that records produced by the simulation demonstrated common features under either highly depositional or highly erosional features, as both would have the effect of obscuring the majority of older dates, leaving the surface consisting of mainly younger dates. Also, as the duration between sedimentary episodes increased, obvious gaps appeared in the simulated chronometric sequences. This was the result of the obscuring processes operating *over the entire landscape*; if this were modulated and a percentage of surfaces remained stable through the sedimentary events, the gaps would disappear. Gaps in this model occur because events either bury hearths or wash away their charcoal; this is a very different mechanism from the more behavioural

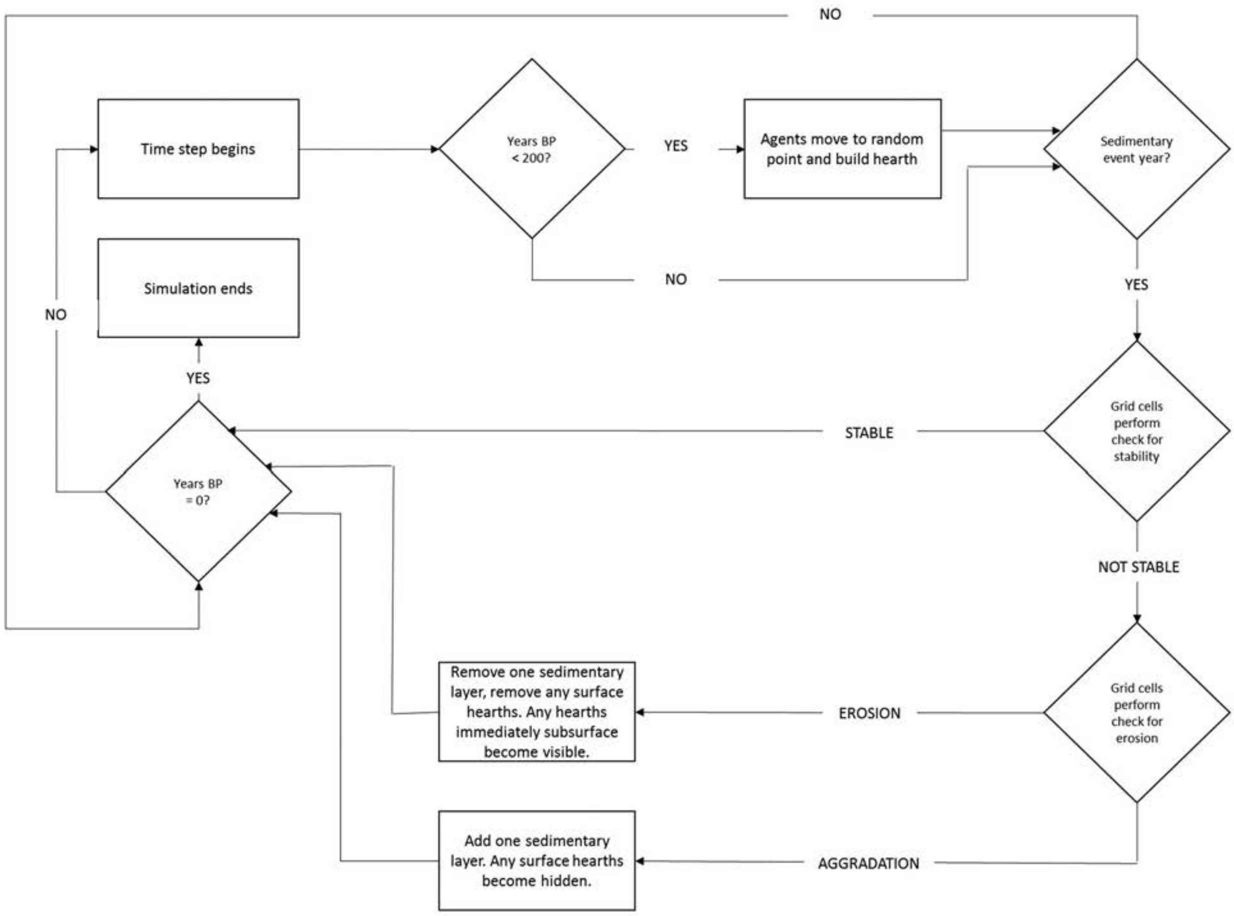

Figure 2. Scheduling of events within the simulation of hearth record formation.

explanation of human absences. This allows a theoretical statement to be made with respect to the simulation and the real world: if the real world operates in a way analogous to that in the simulation, then we would expect that a proxy not similarly effected by erosion would demonstrate a more continuous record if human absences were not taking place.

This theoretical statement was assessed using a second proxy: optically-stimulated luminesce (OSL) dates from hearth stones. The stones, which are heavier than charcoal, are not affected by surface erosion in the same way, remaining mostly in place during low intensity sheetwash erosion (Fanning and Holdaway, 2001). In the simulation, this was accomplished by separately sampling hearths that are visible and contain charcoal (radiocarbon) and those that are merely visible (OSL). The results of this exercise show that the model produces the expected differences between the proxies (Figure 3, grey envelopes). This provides a means of evaluating whether gaps were the product of erosion or human absences, as human absences would be expected to produce gaps in both proxies.

To assess these findings, a set of 106 hearths from Rutherfords Creek were sampled and OSL recordings were obtained (Rhodes *et al.*, 2010). Of those, 103 returned values within the last 2000 years. When compared to the radiocarbon data (Figure 4, black), the curve of the OSL data (Figure 4, grey) is somewhat shallower, but more striking is that periods of time that exhibit substantial gaps or clusters in the radiocarbon data are for the most part absent from the OSL chronology. For example, the clustered period between 367 and 422 BP, containing 25 radiocarbon dates, contains only four dates in the OSL record. If fluctuations in the frequency of radiocarbon dates were due to human population dynamics, then we would expect them to occur in the population of archaeological *features*, rather than their *components*. Instead, the reverse appears to be the case here, which is more in keeping with the mechanics of the simulation.

Discussion

The results of the simulation used above show how a sedimentary system, operating under varying parameterisations of an episodic disequilibrium model

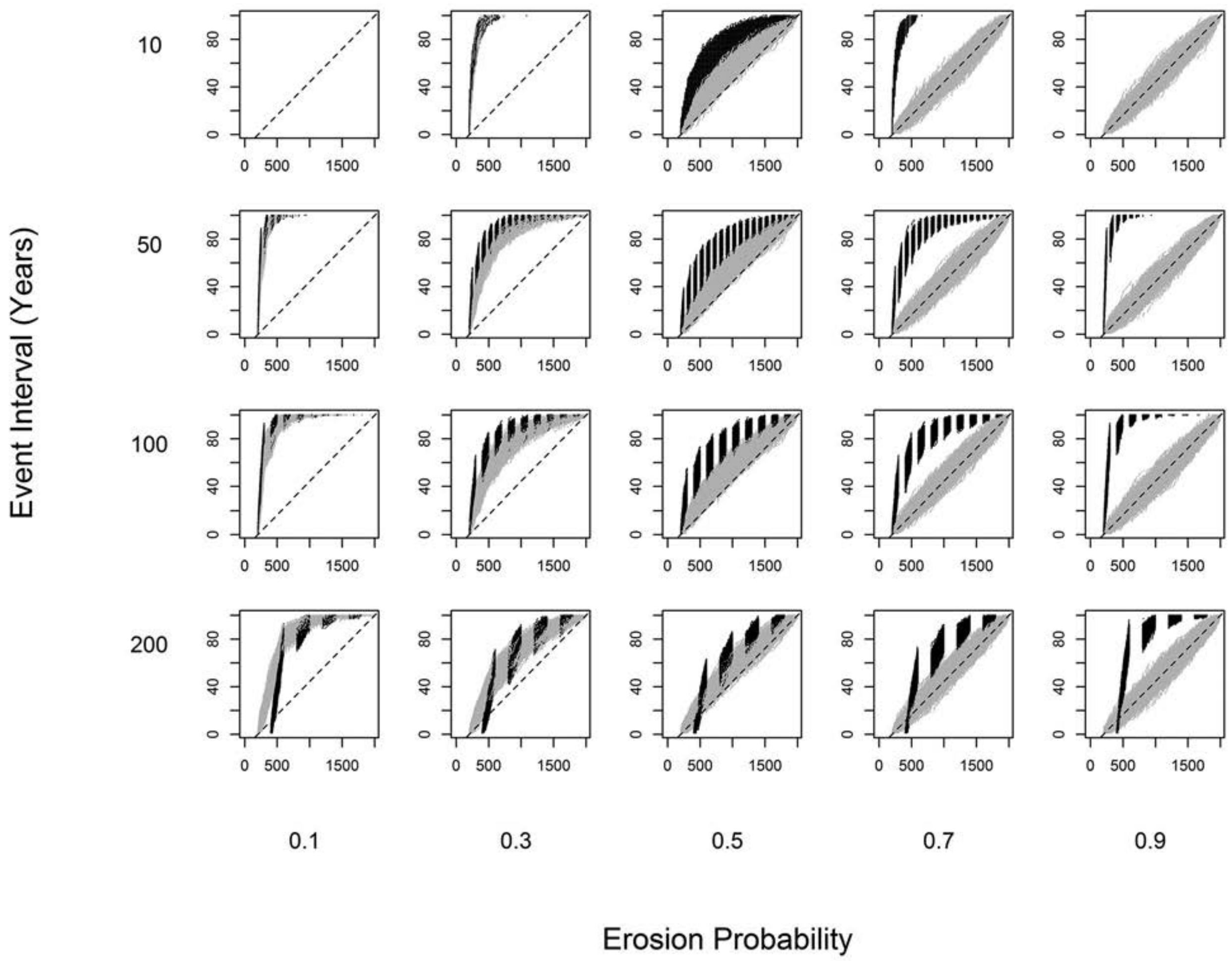

Figure 3. Graphed outcomes from multiple parameter configurations of the simulation. Black envelopes indicate charcoal radiocarbon dates and grey envelopes indicate optical-stimulated luminescence dates from hearth stones. Each envelope contains a plot based on 1000 samples of 100 hearths obtained from simulated surface records.

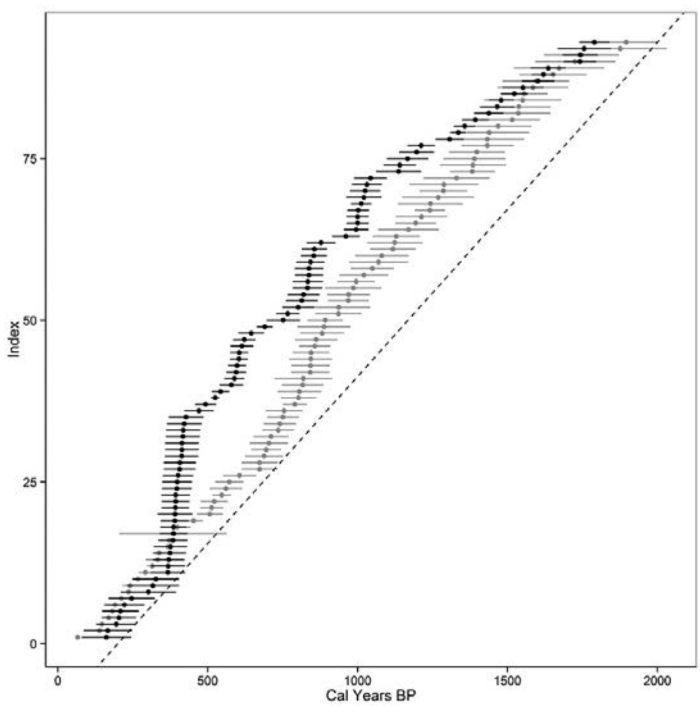

Figure 4. A comparison between calibrated radiocarbon (black, n = 96) dates obtained from charcoal and OSL dates obtained from hearth stones (grey, n = 96). Dates in both proxies are ordered from bottom to top in reverse chronological order. Dots indicate mean age, bars indicate one standard deviation.

(Fanning *et al*., 2007), might affect the archaeological signal of a uniform model of human activity. Sequential sedimentation and/or erosion events over time can transform a steady chronological signal into a record that is biased toward the present and containing episodic gaps. While this is partly an outcome of decay by post-depositional processes operating on deposits over time, the combined effects of differential visibility and preservation has the capacity to produce patterning qualitatively similar to those used to argue for population dynamics in Australian prehistory.

There are three areas that enabled the simulation described above to work effectively as an analogue for the past. The first is simplicity of the underlying model. Bevan (2015, p. 1478) noted recently that the complexity of the past is not itself justification for complicated analyses, urging that '[s]implicity of approach remains a great virtue'. This echoes calls by Premo (2010) for more low-level theory building by way of simple, exploratory models in which the outcomes are well understood with respect to the mechanisms that produced them. The Australian case study uses a model with very simple mechanisms that captured the core logic of geomorphic processes thought to be operating in these creek beds, permitting the assessment of the mechanisms under a range of parameter configurations. This facilitated theoretical statements to be made about the causal relationships between observable sets of activities (i.e. hearth building and sediment movement) and observed arrangements of objects within the simulation (i.e. datable hearths on the surface).

The second is that the patterns of interest within the simulation are produced generatively. This use of the term *generative* derives from the concept of 'generative social science'; a paradigm founded on the notion that, by virtue of the specifications of micro-scale behaviours being known ahead of time, showing a simulation to be capable of generating macro-scale patterning by way of those specifications is sufficient to explain the patterning; put otherwise, 'if you didn't grow it, you didn't explain its emergency' (Epstein, 2006, p. 8). The larger-scale patterning in the case study used here emerges from sets of micro-scale rules (i.e. individual agents build hearths at a given rate, individual grid cells erode or aggrade probabilistically at given intervals). Lake (2015, p. 25), examining the epistemological status of agent-based simulation in archaeology, argues that models should 'be generative with respect to the problem at hand'. This means rather than try to grow all components of a society within a single model, the simulator should be judicious in their selection of what to represent within the model and how to represent it. Rather than try to rebuild late Holocene society in arid Australia, the study here focused on how particular patterns might emerge from an abstracted set of formational processes. This goal is aided by keeping models simple and limiting initial assumptions to as few possible.

The third is that the model is grounded in formational logic. By generating patterning similar to that encountered in the archaeological record, the theoretical statements made based on model mechanics and model outcomes can be applied to the archaeological record in the same analogical way that an ethnoarchaeological or experimental model would. This is not the same as saying that the record is necessarily like that in the simulation, but only that if it were, then findings from the model would be expected to hold true. The theoretical statements generated from the simulation provided a vehicle for asking new questions about the record *were it like that in the simulation*, suggesting tests of the archaeological record itself that helped to compare interpretations.

This is not to say that simulations used to understand the past must always be grounded in specific depositional outcomes as a rule. Insisting on this would only narrow the usage of simulation in archaeology and ignore important lessons from the discipline's history. Theory-building at all levels of abstraction, and the empirical assessment of those theories in terms of their capacity to generate observed patterns in material residues, can benefit from the use of computer simulation. Instead, this is meant as a call to broaden the application of simulation to make more inquiries at the level from which archaeological inferences are drawn: the formation of the deposit. Not all theorising in archaeology should be formational, but no archaeological theory can be successfully applied to the past absent a theory of formation for it stand on.

Ultimately, theory-building at any level is born from the ability to think critically about the way the world works. Recent technological changes have ensured that data is being collected at much higher rates than ever before, often faster than it can be carefully stored and documented it (Bevan, 2015). However, with increasing accessibility of faster computers, free and well-documented software, and programming skills, simulations can be used less as an end unto themselves and more as 'tools to think with'. By keeping models simple, aiming to produce patterning generatively, and connecting theoretical statements to processes that form archaeological patterning, these tools can aide us in using the archaeological record more effectively, and in discerning between competing hypotheses.

APPENDIX: OVERVIEW, DESIGN CONCEPTS, AND DETAILS FOR "WEAVING THE COMMON THREADS"

The following description of the simulation follows the ODD (Overview, Design concepts, Details) protocol for describing individual- and agent-based models (Grimm *et al*., 2006, Grimm *et al.,* 2010). The original simulation was programmed using the NetLogo platform (Wilensky, 1999).

1. Purpose

The purpose of the model is to:

1. Explore surface archaeological formation dynamics by modelling the interaction of individual hearth features within a shifting sedimentary environment.
2. Evaluate the combined influence of preservation and visibility on the chronological distribution of surface archaeological features based on the concept of episodic disequilibrium discussed in Fanning *et al.* (2007).

Additional configurations are used to examine the effects of periodic absence, population growth, and taphonomic decay on the simulated data, as well as the impact of these forces on the surface visibility of stone artefacts.

2. Entities, state variables, and scales

To model the effects of episodic changes in landsurfaces on surface archaeology, two primary entities are used: *hearths* and *patches*. A hearth is an archaeological feature from which chronometric data might be obtained. In the model, hearths are modelled as agents that contain a date, given as the variable `age`, which is the number of time steps that have occurred at the time of its construction subtracted from the total number of time steps over which the model is run ($T - t$). Hearths can exist in one of four states: hidden and intact, hidden and dispersed, visible and intact, and visible and dispersed. Hidden hearths are not considered part of the surface record and thus cannot be sampled in an archaeological survey. Dispersed hearths cannot be sampled using the radiocarbon method.

A patch is a discrete unit of space within a gridded toroidal space (referred to using the more generic term 'cells' in the text but using the NetLogo-specific term 'patches' here). Hearths contain an ordered list of sedimentary layers called `sediment_ages`. Each sediment layer is associated with the date it was deposited. The visibility of any hearths within the patch is determined by their age in relation to the most recent sedimentary later on the patch (i.e. only hearths younger than the youngest sedimentary layer are visible).

A third group of entities, *humans*, are modelled as behaviourally neutral actors that move between random points on the landscape, building hearths at a constant rate of one per year. The use of behaviourally-neutral humans is part of a strategy of model-building aimed at determining the degree of human agency or social complexity required to explain a given phenomenon.

Three parameters are used to control the sedimentary process within the model: the `event_interval` parameter determines the frequency of geomorphic events; the `stability` parameter controls the probability that a patch will undergo some kind of change during an event; and the `erosion_proportion` parameter determines the relative probabilities of a patch undergoing geomorphic change.

The passage of time in the model occurs at yearly intervals, which are tracked forward from a number of years before present using a state variable called `years_bp`. While the simulation is ostensibly meant to model processes at the scale of the 'landscape', the spatial relationships are abstract and not reflective of any particular scale.

3. Process overview and scheduling

During each year, each of the humans moves to a random point within the world and generates a hearth which is visible on the surface and contains an `age` value equal to the current value of `years_BP`. At given intervals, determined by the `event_interval` parameter, an event occurs which affects a subset of all patches. Membership in the subset is determined for patches individually using the `stability` parameter as the probability of change occurring. Patches undergoing geomorphic change determine whether that change is erosion or deposition from a Bernoulli probability draw based on the `erosion_proportion` parameter (see section 6), and this will affect whether hearths on the surface become buried or dispersed, or whether any hearths lying directly beneath the uppermost layer of sediment in the patch become visible. Finally, the `years_BP` value is decreased by one.

4. Design concepts

4.1 Basic principles

The simulation is based on idealised geological and archaeological concepts of stratigraphy and palimpsests. In the model, archaeological deposits exist within stratigraphic layers of sediment. Sediment is transported into and out of a given location by geomorphic processes (e.g. water or wind action). These forces have the capacity to obscure or disperse different elements of surface archaeological deposits.

4.2 Emergence

Regularities in the chronometric distribution of sampled data emerge through the individual-level interactions between patches and hearths. These include super- or sub-linear changes in the frequency of hearth ages, as well as the presence or absence of chronological gaps.

4.3 Interaction

Human agents within the model interact with their environment by adding cultural residues (hearths, artefacts). Patches interact with hearths and artefacts by making them visible or invisible through changes in the sedimentary layers of the patches. Patches also interact with surface hearths by dispersing them in the event of erosion.

4.4 Stochasticity

The movement of agents was modelled as completely random under the neutral assumption of no behavioural bias in the formation of the record. Other elements, such as the probabilities of patches undergoing geomorphic change and the probability of that change being erosional or depositional, are based on Bernoulli distributions, and random number draws are to establish whether these probabilities have been met.

4.5 Collectives

Humans do not form any collective beyond all following the same behavioural rules. Hearths can be grouped based on their visibility and dispersal status.

4.6 Observation

Data was primarily collected at the end of a simulation run. The ages of intact hearths on the surface were recorded to simulate sampling of a radiocarbon record based on charcoal. The ages of all hearths on the surface were recorded to simulate sampling of an OSL record based on hearth stones. For instances where artefacts were included, the mean numbers of artefacts for each patch were recorded. Other data used for debugging purposes included the ages of intact and dispersed hearths that are hidden, spatial distribution of hearths and the number of sedimentary layers in patches.

5. Initialization

When the model begins, all patches contain `sediment_ages` lists with a single value for the start of the modelled time period, equal to the initial value of `years_BP`. The humans within the model are distributed randomly within the modelled space.

Parameter	Setting
world_size	32 × 32
years_BP	2000
starting_population	5
event_interval	10, 50, 100, 200 years
erosion_proportion	0–1 (0.1 intervals)
Stability	0–1 (0.1 intervals)

Table 1 Parameter settings used in the simulation

6. Submodels

6.1 Geomorphic event model

During an event, affected patches will either undergo erosion or deposition, determined individually using a Bernoulli draw:

$$P(n_j) = \begin{cases} 1-p, & \text{for } n_j = 0 \\ p, & \text{for } n_j = 1 \end{cases}$$

where p is the value of the `erosion_proportion` parameter. Patches undergoing erosion will lose the youngest member of their `sediment_ages` list. Visible hearths situated on patches experiencing erosion will become dispersed (`dispersed?` = true), while any hidden hearths situated on an eroding patch that are younger than the youngest member of the patch's updated `sediment_ages` list will become visible (`hidden?` = false). Patches undergoing deposition will add a new value to their `sediment_ages` list, equal to the current value of `years_BP`. Any visible hearths (`hidden?` = false) situated on a patch experiencing deposition become hidden (`hidden?` = true).

7. Alternative configurations

7.1 Stone artefacts

While the original configuration of the model is aimed at understanding these effects of these geomorphic processes on the formation of chronometric processes, the model can be naturally extended to examine how they affect the visibility of stone artefacts on the surface. To do this, patches were given an additional list variable, called `artefacts`. At each time step, after an agent builds a hearth, it adds a value to the `artefacts` list equal to the current value of the `years_BP`. The number of visible artefacts on the surface of a patch at any given time in the model can be calculated as the number of values in the `artefacts` list that are younger than the youngest value in the `sediment_ages` list.

Simulation code can be obtained from https://github.com/b-davies/HMODEL.

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Mieko Matsumoto and Espen Uleberg (eds) 2018. *CAA2016: Oceans of Data*
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Oxford: Archaeopress

Evolving Hominins in HomininSpace: Genetic Algorithms and the Search for the 'Perfect' Neanderthal

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> Man's longing for perfection finds expression in the theory of optimization. It studies how to describe and attain what is Best, once one knows how to measure and alter what is Good or Bad.
>
> (Beightler *et al.*, 1979, p. 1)

Abstract

Genetic Algorithms (GAs) are evolutionary computational techniques inspired by natural selection in which individuals participate in a search for optimal modelling results. HomininSpace (HS) is a large scale realistic agent-based simulation system exploring hominin dispersal through reconstructed landscapes in the deep past. HS implements Neanderthals moving through North–West Europe where simulated presence is scored against dated archaeological sites. A GA is implemented in an automated scan for that parameter combination that produces a Neanderthal agent that best matches the archaeology.

2000 simulations were run with randomly constructed parameter combinations. Each combination of parameter values is taken as an individual. Tournaments are organized to select high potentials, and randomly mixed pairs of successful parents produce hopefully more successful offspring. Simulation results are then added to the pool of individuals that participate in the next tournament rounds. This paper presents preliminary results and the characterization of some very good Neanderthals.

Keywords: Agent-Based Modelling, Genetic Algorithm, simulation, Neanderthal

Introduction

Optimisation of agent-based models is generally seen as a complex problem. Computation of a solution involves the execution of a simulation in all but the most trivial models. The search for optimal solutions is therefore computationally expensive, especially when the level of realism is high and the number of parameter combinations is large. This research applies Genetic Algorithm based search and optimisation techniques in an attempt to characterise Neanderthal mobility using a realistic large scale agent based modelling system. The methodology and software developed in this study are part of the doctoral research of the author.

Genetic Algorithms

Genetic Algorithms (GAs) form, together with Evolutionary Strategies and Genetic Programming, the Evolutionary Algorithm programming paradigm (Coello Coello, 2002). Differences between these techniques are fading (Michalewicz, 1992, p. 132), and while the chosen terminology no longer reflects our current understanding of genetics, they all aim to simulate an evolutionary process in the computer (Coello Coello, 2002). Basic elements in evolutionary algorithms are a population of individuals to work with, a string with values that define an individual which can be manipulated (referred to as the genes or the chromosome), a fitness function that calculates how well adapted an individual is within the modelled environment (Michalewicz, 1992), and an optimisation technique targeting optimal solutions.

The term Genetic Algorithm (GA) was coined by John H. Holland (1975) but the general principle was already recognized by Alan Mathison Turing in the 1948 essay 'Intelligent Machinery': '*There is the genetical or evolutionary search by which a combination of genes is looked for, the criterion being the survival value*' (Turing, 1948, p.18). The idea is that an individual represents a single solution to the problem at hand; that individuals vary from one to the other; that an evaluation function represents the environment in calculating the fitness of each individual; and that the computer searches for the individual with the highest fitness value (the optimal solution) in the problem space, without actually programming that solution, but instead by manipulating the genes of the individuals (Coello Coello, 2002).

GAs are very well adapted for nonlinear search spaces, with multiple locations present in those spaces that can yield good solutions. A non-traditional methodology is required when traversing these resulting parameter spaces searching for an optimal solution, where exhaustive search algorithms are replaced by a heuristic procedure. A GA differs from more traditional optimisation and search algorithms in at least four ways (Goldberg, 1989):

1. A GA searches in a population of points, not just a single point;
2. GAs operate with probabilistic, unbiased transition rules, not deterministic ones;
3. A GA operates on a set of parameter values, not the parameters themselves, and does not require any explicit knowledge of the actual structure of the solution space (what these parameters are about);
4. A direct, explicit fitness function is used.

For the structure of a GA, a probabilistic selection is made from the population based on some measurement of the individual's adaptation to the environment or its fitness within it. The design of the fitness function is at the discretion of the modeller. After the selection of one or more individuals, operators are applied on the selection. These operators are inspired by the early perception of how the genomes of offspring were created in nature. They include Mutation, where random changes are made to the genes of an individual, and Crossover (a special kind of Recombination), where the genes of two individuals are mixed in sequence. Then the fitness function is calculated for the generated offspring, and the new individuals are inserted into the population, generally replacing other individuals. The process is then restarted, until some stop criteria are met. Generally the stop criterion is a certain value for the fitness function being attained, or no measurable improvement of the calculated fitness values after a certain number of generations.

Agent-Based modelling

An Agent-Based Model (ABM) is a complex system aiming to reproduce the dynamics of the real world, and one that cannot be solved mathematically. Therefore GAs form a perfect exploration and tuning method for such models (Calvez and Hutzler, 2006). Emerging properties, high parameter sensitivity, and non-linear solutions often characterise the solution space for such models. There is no analytical description, and simulation results cannot easily be reduced to the input data. There is development and emergence in a non-trivial way. As such they are well suited to modelling complex systems and to explore this complexity. Archaeological research questions connected to such models often incorporate the resultant output of the (inter)actions of many individuals through time, and as such can be targeted by ABM techniques (Lake, 2014). However, there have been few attempts to apply GAs to archaeological simulations, although they are implicitly used in the more widely applied Genetic Algorithm for Rule-Set Prediction tool (GARP) for biogeographical niche modelling (Banks *et al.,* 2008).

HomininSpace

HomininSpace is an agent based modelling and simulation environment where a fluctuating carrying capacity in a reconstructed paleoenvironment is the key attractor for hominin dispersal (Scherjon, 2015a). Simulations executed in the HomininSpace modelling system are used to assess the character of past hominin dispersal, taking the patterns of presence and absence of Neanderthals in North–West Europe in the Middle Palaeolithic (130 kya–50 kya) as a case study. Mobility, the sum of small scale movements through larger geographic and temporal scales, enables hunter gatherers to survive (Kuhn *et al.,* 2016).

Energy in the landscape, in the form of herds of medium to large ungulates, will support groups of Neanderthals moving through the reconstructed environment. That environment includes a topography influenced by fluctuating sea levels. The question is whether the dispersal and movement of Neanderthals was based on tracking preferred habitats. The tracking of favourable habitats has also been described as the 'ebb and flow' of populations (e.g. Hublin and Roebroeks, 2009), and involves individuals or groups of individuals moving in the area where the most favourable circumstances are found. Today the best known example of such behaviour is displayed by migratory birds, which fly south towards the Mediterranean or beyond in autumn and return when spring sets in.

The 'ebb and flow' of moving populations has often been opposed to a 'sources and sinks' model, where local populations must adapt behaviourally and/or genetically to cope with the changing climate or subsequently become extinct when conditions become less favourable (Pulliam, 1988, 1996). They are replenished from more productive areas when the situation improves (MacDonald *et al.,* 2012). Obvious examples of this 'sources and sinks' model are most species of flora. Since individuals of this kind cannot move by themselves, they invariably die when the climate deteriorates too far. For that species to live there again, the area must be re-colonized from other areas where local reproduction more than balances mortality. The question is whether Neanderthal dispersal patterns more closely resemble ebb and flow movement or a sources and sinks model.

To address the mobility of Neanderthals, the two opposing types have been implemented in the parameterised model (16 parameters in total) underlying the HomininSpace simulation system. These types are termed Static and Dynamic. Simulations are executed for both types and a fitness function, and have been constructed to compare simulation results with the archaeological data. This fitness function counts and totals how often an archaeologically determined presence period is matched by a presence in the simulation at the same point in time. A period of presence is defined as the radiometrically determined date (with standard deviation) for an artefact or for sediment associated with the archaeology. For instance, it has been shown that Neanderthals were present in Pech de l'Azé IV with a thermoluminescence (TL) measurement on heated flint (Richter *et al.,* 2013). This artefact is dated to 68.5 kya, with a standard deviation on this TL date of 6.6 kya. If in any simulation a Neanderthal group is within the area of Pech de l'Azé IV during the period 75.1–61.9 kya, each year of that presence is counted and added to the total simulation score. This sum is referred to as the MatchingVisits, and is the quantitative fitness value for that specific simulation (Calvez and Hutzler, 2006, p. 47). Initial results presented in earlier research suggested that for manually selected parameter values, the Static mobility type produced the best solution, or in other words that simulation results for Static hominins matched the Neanderthal archaeology best (Scherjon, 2015a).

Each simulation is characterised by a combination of parameter values and a fitness value that is the result from running the simulation with those parameter values. This combination of parameter values is referred to as the *chromosome* for that individual simulation. GAs are then used to search for the parameter value combination that matches the archaeology best. An initial population is constructed by varying parameter values randomly, and then running the simulations with these parameter sets. Then, individual simulation results are used to select promising parameter combinations, running new simulations for the generated offspring in a search of the optimal solution.

This rest of this paper is structured as follows: the next section will describe the implemented GA and the underlying data set. Then, results for the experiments are provided and discussed. The conclusions are presented in the last section, together with some directions for further research and suggestions about future use of genetic algorithms in archaeological ABMs.

Materials and methods

In this research the following steps were implemented:

1. The construction of a list of one thousand randomly created parameter sets that can be used as input to the HomininSpace modelling system. Default values for the parameters were selected from the literature, and the random values for the parameters were generated within the interval of 10%–200% of that default.
2. The creation of simulation results from two initial populations; one of Static and a second of Dynamic hominins. This involved running all 1000 parameters sets constructed in the first step for both mobility settings, and calculating the fitness value for each combination for both settings.
3. Run GAs for both initial populations, using as selection criterion the match with the archaeology. As two variants were applied to the Dynamic hominins, the result is three data sets.
4. Analyse these three data sets to find the most optimal solution, or the 'Perfect Neanderthal'.
5. Explain the results, using correlation analysis on the initial populations and computation of the coefficient of variation for the results from the GAs.

The parameters that are used in the model underlying the HomininSpace (HS) modelling system are described in Table 1. There are 16 parameters in total, distributed in three groups: those for Demographics, for Energetics and one for Group Dynamics. Parameters are based on ethnographic data (default) with wide plausible extended value ranges, from which instance values are randomly selected. Employing these 16 parameters, if you need to systematically explore the total parameter space, this can exponentially expand the number of parameters. For example, if you take only three values per parameter (a minimum, a maximum and a middle value), this would require the simulation of a 3^16 parameter set (or almost 300 million simulations). Therefore the combinatorial explosion with so many parameters requires a non-exhaustive exploration. Nevertheless, due to the non-linear character of the solution space, an automatic and systematic exploration of parameter space is needed (Calvez and Hutzler, 2006).

The implemented GA in the HS system selects individuals from the population using a tournament selection procedure (Miller and Goldberg, 1995). For the selection of each individual, a tournament is organised in which *n* random individuals are chosen from the population. From this subset the highest ranking (most optimal) solution is declared winner. This procedure ensures that even mediocre solutions can produce offspring. The selected individuals participate in the creation of the next generation of seven new individuals through the application of several operators. HS implements a real-coded GA where each individual is represented by a string of 16 integer values, one for each model parameter (Herrera *et al.,* 1998). Then additional simulations for the newly

#	Parameter name	Description	Default
	Demographics		
1	Birthrate	The number of females that conceive this year (percentage)	33
 2 3 4	Deathrate per cohort - pre fertile - fertile - post fertile	The percentage of individuals that do not survive to the next year (percentages per cohort)	 4 3 8
 5 6	Cohort size - pre fertile - fertile	Size in individuals for the pre-fertile and fertile cohorts.	 13 30
	Energetics		
7	Calories per kg meat	The number of calories that can be extracted from a kilogram of meat.	3000
 8 9 10	Subsistence per cohort - pre fertile - fertile - post fertile	The required number of calories for each cohort. If less is available, the group is hungry.	 3000 4000 3500
11	Temperature tolerance	Minimum temperature in degrees Celsius that the group can survive.	-18
	Group dynamics		
12	Years before group interaction	The first *n* years a group cannot interact (merge, settle) with other groups.	5
13 14 15	Min group size before merge Min cohort size fertile before merge Max group size before split	If group size fall below, the group will attempt to merge. If the fertile cohort falls below this size, merger is attempted. If the group size exceeds this, the group will split.	10 3 50
16	Max Foraging Range	The maximum range that the group can exploit, in grid cells.	5

Table 1. The parameters for the modelled hominins in HomininSpace.

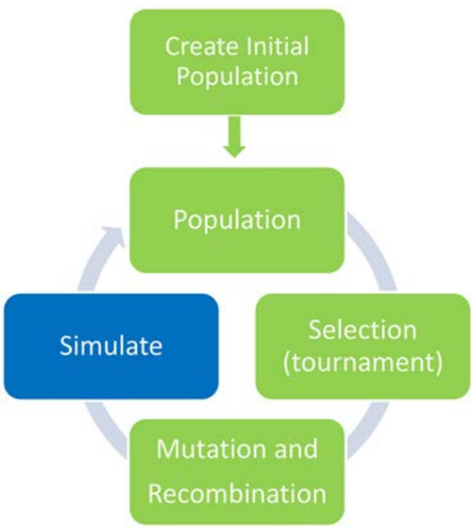

Figure 1. Application of Genetic Algorithms in the HomininSpace modelling system.

generated parameter combinations are executed, the fitness value computed, and the offspring is added to the general population. This process is repeated until the end of each experiment (see Figure 1).

The operators that are applied are crossover and mutation. Mutation is implemented as the random modification of one single parameter value by plus or minus 10%, and thus implements a low rate mutation mechanism to increase coverage of the search space and to prevent convergence to a local optimum (Yao, 1993). An additional advantage of the chosen mutation operator is that when needed, the search space can be expanded even beyond the original chosen random value domain. In other words, values can be created that are not present in the (initial) population (Djurišić *et al.*, 1997). Crossover aims to recombine two good parent solutions into potentially even better offspring

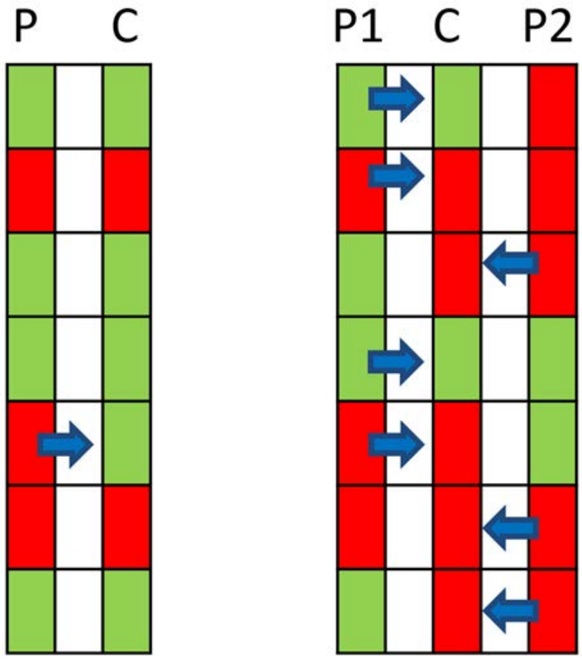

Figure 2. Mutation operator (left) and uniform crossover operator (right) producing offspring individuals (denoted by C).

solutions. Implemented is a uniform multi-point crossover, where the offspring is a single individual that is a stochastic mix of the parameter values from both parents (Syswerda, 1989). This combines very well with tournament selection (Djurišić *et al.,* 1997, p. 7860). Seven individuals (four crossover results, three mutations) are created in each generation, because the hardware running the experiments has seven parallel processors available for executing simulations.

Since offspring is added to the population without any replacement of parents or other less performing individuals, no lineage is terminated prematurely, and each individual competes until the very end of each experiment. This also ensures that the best performing individuals survive intact within each generation. However, successful lineages tend to dominate the tournaments, which can be used to create an informed stop criterion for the GA.

Results

Two experimental setups were created: one for Static hominins (those that stay in the same area even when the climate deteriorates) and one for Dynamic hominins (that constantly move to that area that has the most resources). In each experiment, initial populations were created by running 1000 simulations with randomly created parameter values (the same values for both experiments). The fitness value (referred to as MatchingVisits) is shown for both experiments in Figure 3. Static results are first plotted and then overlain by Dynamic results. Most obvious are the overall green peaks, suggesting the more optimal solutions are for Static hominins. Of interest are the simulations with better Dynamic results, which in Figure 3 are the results in red peaks, with some more promising results highlighted in blue in the figure. These two sets are used as input for the GAs, for which the results are presented below.

However, first a characterisation of the parameter influence is undertaken by calculating a Pearson product-moment correlation coefficient (PCC) for each parameter against the fitness value, in both experimental starting populations. The PCC gives the degree of linear dependence between two ratio-scale variables, and can be a positive, a zero or a negative correlation (Fletcher and Lock, 2005, p. 117). These results are presented in Table 2. For Static hominins the Birthrate, Max_ForagingRange and to a lesser extent the CohortSize_Fertile are positively correlated. In addition, negative correlations are especially clear in DeathRate_PostFertileCohort, and also to a lesser extent in DeathRate_PreFertileCohort, DeathRate_FertileCohort and GroupSizeFertile_BeforeMerge. For Dynamic hominins, a positive correlation was found for Max_ForagingRange, Birthrate and GroupSize_BeforeSplit. There is a negative correlation between fitness value and DeathRate_FertileCohort, GroupSizeFertile_BeforeMerge, and Temperature_Tolerance.

GAs were executed for both experimental setups. For the Static hominins, 731 new individuals were generated. The stop criterion was an experiment duration of two weeks, and no further improvement after 13 generations (>100 individuals). The maximum value of 3,945,109 was obtained in simulation number 1638. For Dynamic hominins, 540 extra simulations were run. Here the maximum of 3,948,133 was reached in simulation 1495, and after an additional 45 simulations with no improvement the experiment was ended (end result higher than Static max). In total 3271 simulations were executed, with an average execution time of 20 minutes per simulation.

The top 5 results for both experimental setups are presented in Table 3. To illustrate the effect of the optimisation effort that GA can achieve, the best results from both initial populations are also included. It shows that improvement is especially spectacular for Dynamic hominins; changing from a maximum score of 2.4 m to 3.9 m (where Static hominins achieve an improvement from 3.5 m to 3.9 m). These results can be compared against results from previous research (Scherjon, 2015b) where manually constructed parameter combinations were executed for both Static and Dynamic hominins

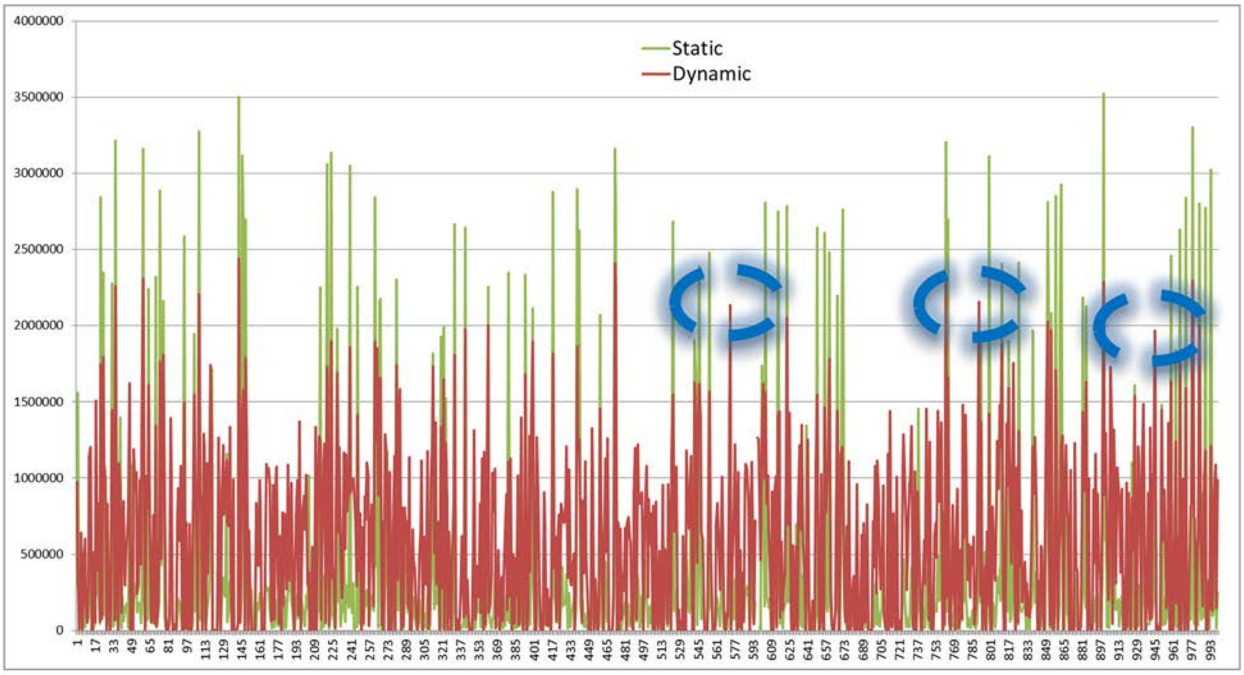

Figure 3. Results for the simulations of the initial populations for both experimental setups. On the vertical axis the score for MatchingVisits, and on the horizontal axis is the simulation number. For each simulation two results are plotted; for Static in green and for Dynamic in red. In the circles there are three Dynamic peaks, meaning that for those simulations Dynamic scores higher than Static.

Parameter	Static	Dynamic
Birthrate	0,274 (**)	0,255 (**)
DeathRate_PreFertileCohort	-0,106 (**)	-0,054
DeathRate_FertileCohort	-0,382 (**)	-0,387 (**)
DeathRate_PostFertileCohort	-0,88 (**)	-0,020
Subsistence_PreFertileCohort	-0,075 (*)	-0,038
Subsistence_FertileCohort	-0,034	-0,020
Subsistence_PostFertileCohort	0,030	0,038
Years_Before_Group_Maturity	0,008	0,009
GroupSize_BeforeMerge	0,056	0,033
GroupSizeFertile_BeforeMerge	-0,133 (**)	-0,133 (**)
GroupSize_BeforeSplit	0,025	0,126 (**)
Temperature_Tolerance	-0,039	-0,216 (**)
CohortSize_PreFertile	-0,064 (*)	-0,048
CohortSize_Fertile	0,093 (**)	0,027
Calories_Per_Kg_Meat	0,005	0,006
Max_ForagingRange	0,321 (**)	0,543 (**)

Table 2. The Pearson correlation coefficient for each parameter against the MatchingVisits fitness value. ** denotes a significant correlation, which for easy reference is also colored red. Parameter names are taken from the source code.

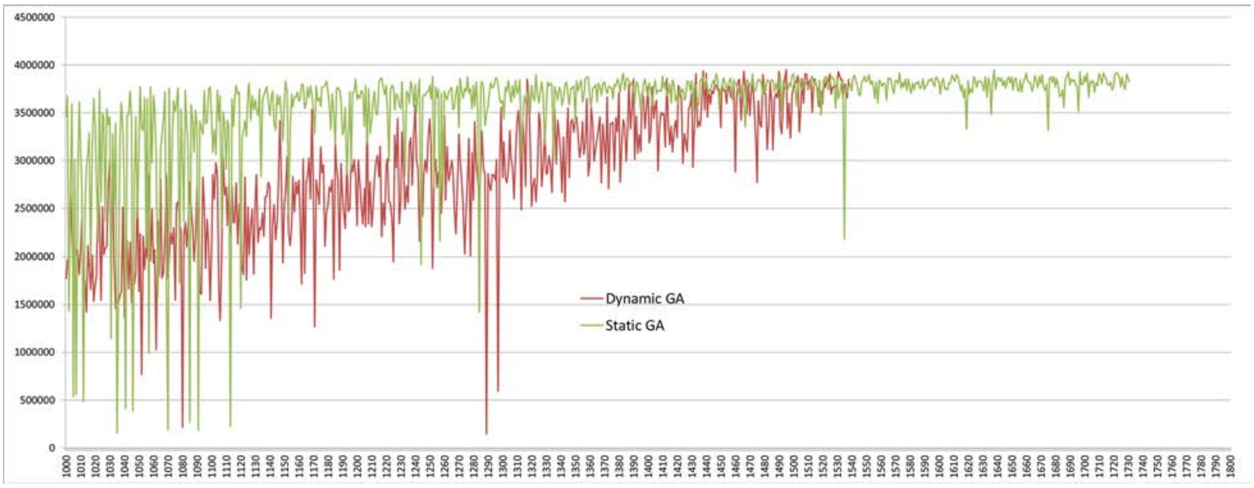

Figure 4. GA results for both Dynamic (red) and Static hominins (green).

Rank	Dynamic	Static	Dynamic no GA	Static no GA
1	3948133	3945109	2439862	3525472
2	3936292	3927346	2409498	3501416
3	3934425	3926433	2307478	3300544
4	3934235	3918835	2293627	3276385
5	3928542	3916597	2284907	3213257

Table 3. Top 5 results for both Dynamic and Static hominins, results with and without GA optimization.

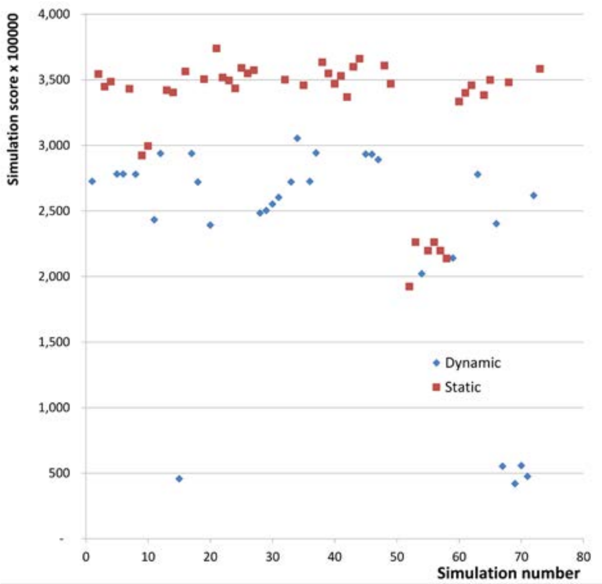

Figure 5. Taken from Scherjon (2015b). For each simulation the simulation scores for Static hominins are better than those from the corresponding (same parameter value) Dynamic simulations. The simulation score quantifies the match with the actual archaeology.

(Figure 5). Parameter values here were derived from the ethnographic literature and modified slightly to accommodate expected Neanderthal deviation (for instance, energy usage was increased, see Verpoorte, 2006). Although the implemented system was subsequently further developed, the general trend was clear: for the manually constructed parameter sets, Static simulations always scored higher than Dynamic (comparable to most of the non-GA optimized results presented in Figure 3). In that research, no higher scoring Dynamic simulations were found.

Discussion

The results from previous research in Scherjon (2015b) that are reproduced in Figure 5 were explained to a large extent by the more intense resource competition that would result from Dynamic behaviour. Areas with many resources would attract all hominins from the surrounding area, who would then deplete the resource patches, with resulting food shortages for all. Apparently, though, there are hominin types that follow a Dynamic strategy and that do show a good (and even best) match to the archaeology (Table 3).

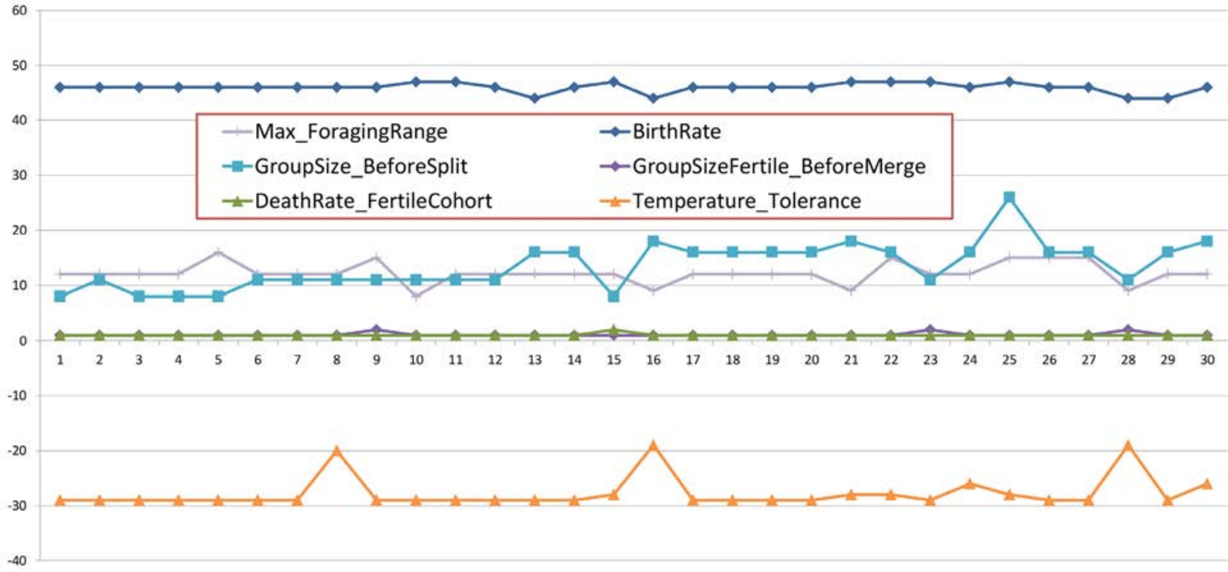

Figure 6. The top 30 Dynamic hominins, for all significantly correlated parameters.

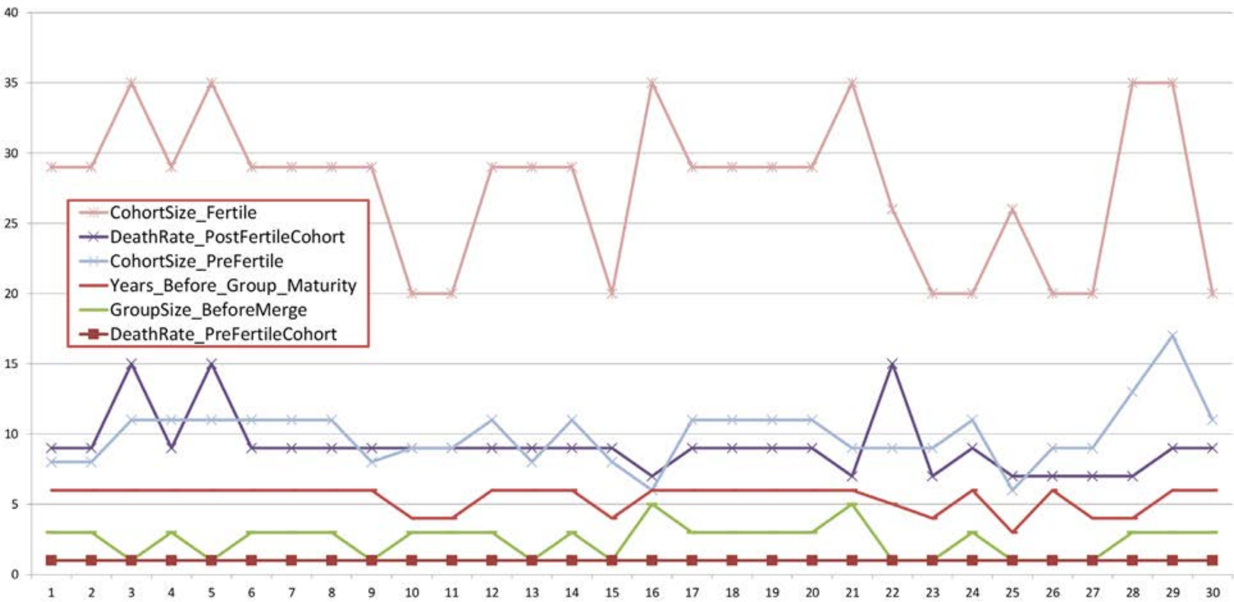

Figure 7. The non-significant parameters for the 30 best ranking Dynamic simulations.

To characterise these dynamic hominins, the values for all significant parameters for the 30 most optimal solutions implementing the Dynamic mobility pattern are presented in Figure 6.

Figure 6 shows that the most successful Dynamic hominins all have a relatively high birth-rate, around 46% (dark blue line). It also shows that the difference between number 1 and number 2 is only a slight decrease in the variable GroupSize_BeforeSplit, the variable that indicates when groups become unstable (note that there can be other differences in the non-significant variables). This variable is also the most variable one. Also observe that the value suggested in the literature is 25 (Sørensen, 2009), which here is only sported by the 25th ranked Dynamic simulation.

To understand these results further, it is important to realise that the fitness value is constructed by matching with *presence* data in the archaeological record. These data points are spread through the simulation area, both in space and time. The theoretical best match would be attained by a hominin that is present everywhere all the time (!). Such a hominin cannot be sustained by the limited amount of resources produced by the environment. So the system, implemented in a GA, searches for a sub-optimal solution, and detects a family of solutions that represents a hominin type which is not, as such, recognised in the literature. This is a hominin that constantly travels through the landscape within very small groups (around ten individuals) and with a very high birth-rate (close to the physical limit a female modern human body would be able to sustain, around 46%).

When inspecting the non-significant parameters for the same set of solutions (Figure 7), it becomes clear that values for these vary more than for the significant parameters. This makes sense since they influence the final result less. Contra-intuitive energy related variables are also non-significant for scoring against the archaeology (not included in the figure).

Conclusions

A Genetic Algorithm (GA) has been implemented in the HomininSpace simulation system (HS) to systematically explore the parameter space that results from the chosen parameter set in the underlying model. Simulation results are compared against an archaeological record of actual presence data, resulting in a quantitative fitness value per simulation. It is shown that the implemented GA is capable of finding more optimal fitting parameter value combinations that result in a higher fitness value than informed manually selected parameter values. When applied to the research question on Neanderthal mobility, it must be concluded that the results for both strategies are very comparable. The fitness values for improved individuals are within the same order of magnitude, and there is no statistically significant difference between Static and Dynamic hominins (contrasting previous research). However, it is interesting that the best matching simulations were those which, by a narrow margin, have hominins that are implementing a Dynamic mobility strategy.

The model not only implements the mobility type, but also many other parameters involved. This results in the following characterisation of the most optimal fitting solution in the model underlying HS. The 'perfect' Neanderthal:

- implements a Dynamic mobility strategy;
- has a (very) high birth-rate;
- sports low death rates for pre-fertile and fertile segments;
- has high death rates for the post-fertile segment;
- has a low energy intake;
- can resist cold fairly well;
- has a short childhood;
- operates in relatively small groups;
- hunts and collects from a large foraging range.

From these results it can be concluded that the implemented Genetic Algorithm works. It improves upon randomly constructed initial population results and falsifies previous research: the evolved Dynamic Neanderthals have an equal or better fit than all Static ones (evolved or manually constructed). The search for optimal solutions is generic, systematic and produces better results than informed manual selection of parameter values. The character of the parameter values for the set of most optimal solutions confirms the statistical analysis on the significance of certain parameters on the fitness value. This information can be used in future parameter reduction efforts on the model, but care must be taken; some parameters which are unimportant in some simulations, might be important in others, and vice versa (for example see the Temperature_Tolerance and the death rate for the post-fertile cohort parameter).

Genetic Algorithm techniques applied in ABM are, unfortunately, computationally expensive, since the calculation of the fitness value is the actual simulation run with the evolved parameter set. Therefore the following elements must be considered carefully when constructing a GA for an archaeological ABM: the total computational costs, stochasticity in the genetic algorithm, choice of GA operators, the stop criterion and the chosen fitness function. And as with all stochastic modelling: nothing is guaranteed!

It is acknowledged that the simulation results are matched against presence data only, and this has a major impact on the direction of the search for optimal solutions. The best match with the archaeology would be achieved by a simulated hominin that is present everywhere all the time. Such is a general issue when using archaeological data, since 'absence of evidence is not evidence of absence' (Phillips *et al.,* 2006). However, archaeologists are quite convinced that Neanderthals were not present in certain areas at certain points in time during the simulated period (Ashton, 2002; Wragg Sykes, 2017). Further research should take into account the tendency to fill the landscape when presence only information is used and should investigate the effects of incorporating evidenced absence.

Acknowledgements

Research by Fulco Scherjon was supported by the Netherlands Organisation for Scientific Research (N.W.O. Spinoza program). I thank three anonymous reviewers for their useful suggestions which significantly improved the paper and the editors for their efforts in checking the details.

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Mieko Matsumoto and Espen Uleberg (eds) 2018. ***CAA2016: Oceans of Data***
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
Oxford: Archaeopress

An Agent-Based Approach to Weighted Decision Making in the Spatially and Temporally Variable South African Paleoscape

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Abstract
Even a simple human foraging system has a large number of moving parts. Foragers require a complex decision making process to effectively exploit the spatially and temporally variable resources in an environment. Here we present an agent-based modelling framework, based in optimal foraging theory, for agent foragers to make mobility and foraging decisions by weighing expected caloric returns against geographic and social factors, and forecasted future return rates.
We apply our Paleoscape model to a spatially explicit South African coastal landscape to better understand the human foraging system of the Middle Stone Age, when foragers began systematically exploiting a wide variety of flora and fauna in both terrestrial and inter-tidal environments. We also discuss the broader importance of agent-based models of foraging systems for a wide variety of archaeological research questions.

Keywords: agent-based modelling, optimal-foraging theory, middle stone age, marine foraging

Project purpose and background

A basic tenet of the behavioural ecological approach to anthropology is that local ecology, the density and distribution of resources in time and space, determine optimal patterns of economic exploitation of resources. Those optimal foraging, mobility, and grouping patterns then constrain all other aspects of social behaviour, and interact with mating patterns and social norms to produce the core behaviours of society. As such, it is of primary importance that anthropologists develop and test hypotheses about how resource patterning results in basic human economic patterns.

The Paleoscape project was conceived of as a detailed and empirical attempt to reconstruct the hunter-gatherer system during several temporal phases in a coastal South African region. From the outset of the Paleoscape project, we have used optimal-foraging theory (OFT) as a theoretical base with well-established literature to design our agent-based modelling approach (see also Lake, 2000; 2001). The aim is to use this reconstruction to explore a large number of hypotheses related to human behavioural change. Pinnacle Point, Blombos Cave, and Klasies River Mouth are a set of South African coastal archaeological sites and localities well known for behavioural firsts for *Homo sapiens*; the earliest use of shellfish for food, heat-treatment of stone for lithic manufacture, and ochre for pigment at 162 ka (Marean *et al*., 2007; Brown *et al*., 2009), and some of the earliest beads at 72 ka (Henshilwood *et al*., 2004), among many others. As such, the context for these behavioural changes has come under close scrutiny as they relate to both the behavioural evolution of our species, as well as our expansion out of Africa into the rest of the world relatively shortly after this pivotal period. The context must be conceived broadly to encompass the climate, ecology, and human social behaviour. In previously published articles we have spelled out this broad research project in detail, including the significant progress made so far (Marean *et al*., 2015; Shook *et al*., 2015).

The model described in this paper has a rather broad purpose, but is intentionally designed in a rather simple way. This paper will present our reasoning behind the development of this model, its design and current implementation with a particular emphasis on the core mechanism, and an illustration of its potential results. A larger treatment of the empirical data, model runs, and its broader implications for the archaeological record is currently in preparation.

The Agent-Based Model (ABM) described below serves as an endpoint in the collection of a large amount of empirical data collected from specially designed

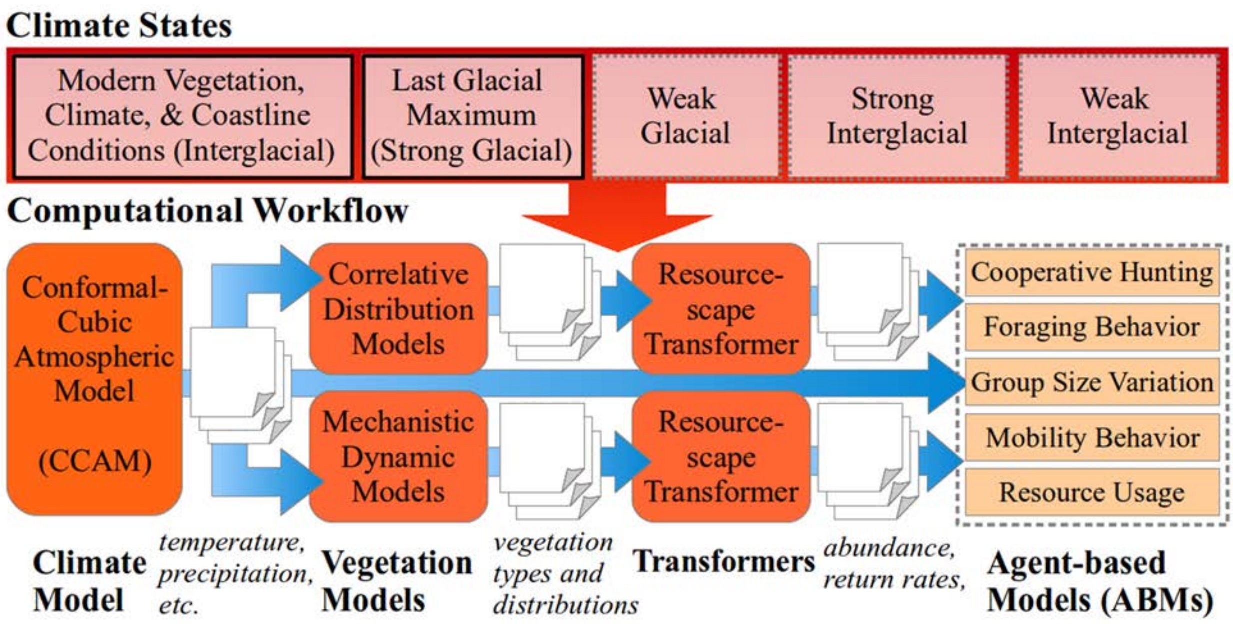


Figure 1. Computational workflow of the Paleoscape Project. Climate, vegetation, and human foraging models are connected using established theory to simulate past human-environment systems during several different temporal phases (reproduced from Shook *et al.,* 2015, Figure 1).

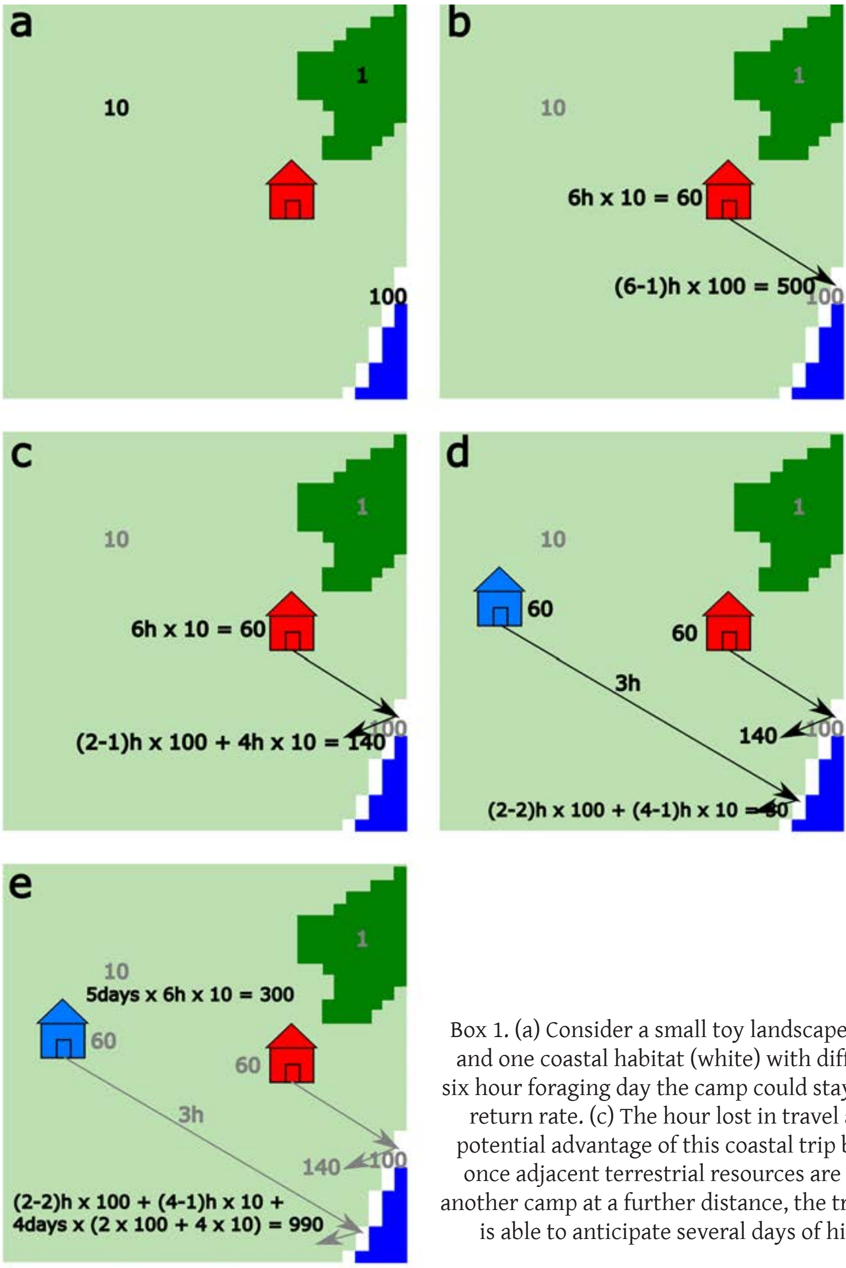
fieldwork and literature reviews (Figure 1). As such, the ABM must be both detailed and flexible enough to accommodate this.

Foraging as base ABM type

An additional purpose of this paper is to outline the importance of a key agent based modelling subject for archaeological research; that of a foraging system. A foraging system is the pattern of mobility and collecting decisions hunter-gatherer groups follow to collect the resources they need: food, water, shelter, stone and other materials for making tools, wood for fuel, and even ochre for pigment production. This should not be surprising given the importance of foraging to interpreting behaviour from the archaeological record. However, this commonality has not been explicitly highlighted in archaeological ABMs to our knowledge. We argue here that the foraging ABM is a kind of base ABM type that underlies questions related to hunter-gatherers' settlement and mobility patterns at the local scale, dispersal at regional and global scale, human-environment interactions, behavioural and biological evolution, inter-group interaction, exchange systems, coping with risk from climatic and ecological change, among many others (see Lake, 2014 for a survey of published applications). Since foraging underlies all of these research questions, there should be a systematic focus on the commonalities between the agent-based modelling efforts related to addressing these questions. We will present a beginning to that effort here.

As noted above, OFT is a set of simple models offering a coherent framework for understanding how and why different foraging choices are made within a resource landscape. OFT assumes foragers make choices which maximize a specified fitness-related currency (such as calories) given a known set of available resources, time constraints, costs, and benefits. In these cases OFT models help predict which resources will be collected, how much time should be spent collecting, how many species should be hunted, and so on (Stephens and Krebs, 1986; Winterhalder and Smith, 1981). OFT rigorously defines entities such as habitats, resource patches, and prey items which will be important for our modelling approach. Janssen and Hill (2014) describe in detail the limitations of classic OFT for modelling foraging systems and the advantages of using an ABM approach. For example, the cumulative effects of foraging over long-time scales is better suited to ABM than an algebraic OFT model, as is the effects of inter-group interactions. The ABM framework also allows us to experiment with decision making algorithms designed to reflect different behavioural assumptions and to evaluate their relative effects.

Using OFT as a theoretical base has also helped to guide our empirical data collection efforts by determining what data is needed to reconstruct and evaluate a specific foraging system. Over the past few years, this has led our broader research team to a large number of field and literature surveys into the amount of time required to search, gather, and process resources, travel



Box 1. (a) Consider a small toy landscape with two terrestrial habitats (green) and one coastal habitat (white) with different return rates in kcal/h. (b) In a six hour foraging day the camp could stay put or move to the coast for a bigger return rate. (c) The hour lost in travel and the two hour low tide limit the potential advantage of this coastal trip but is still worth the move especially once adjacent terrestrial resources are harvested after the low tide. (d) For another camp at a further distance, the trip is not worth it (e) unless that camp is able to anticipate several days of high returns during the Spring tide.

speeds, and the caloric returns of resources in the study region including shellfish (De Vynck *et al*., 2016a), plants (Singles *et al*., 2016a;2016b; De Vynck *et al*., 2016b; 2016c), and terrestrial mammals.

How do you model a forager?

To blend OFT with the ABM, we base agent decision making on an algorithm designed to make optimal foraging decisions based on maximizing caloric returns within the available daily foraging time (for a similar approach see Lake, 2000, 2001). However, there are a number of complicating factors which are generally relevant to hunter-gather foraging systems, as well as to our agents' decision making in particular. Firstly, resources are spatially variable requiring the agents to account for the net caloric return after travel to a known resource. Secondly, resources are temporally variable requiring agents to not only assess the current resource state, but also to predict when resources will be available before they actually are. This is particularly important given the dramatically different return rates of shellfish based on tide heights driven by lunar cycles (Marean, 2010, 2011, 2014; De Vynck *et al*., 2016a), but also relates to the seasonal availability of plants, and migratory patterns of some terrestrial mammals. Thirdly, foragers are social and are embedded in systems of cooperation and food sharing within and between groups (Janssen and Hill, 2014, 2016).

Data

A fuller treatment of the data gathering efforts involved in the Paleoscape project is currently in preparation.

Here we will simply outline that we have divided up the study region into ecological zones and are undertaking a systematic survey of plant, shellfish, and terrestrial mammal food resources, as well as additional resources such as wood for fuel and raw material for tool making. In each case, through literature reviews and specifically designed in-field experiments with Khoi-San descendants of the region, we have collected data on caloric return rates, and searching and processing times for parameterising the ABM (see table S2 and methodologies in De Vynck *et al.,* 2016a; 2016b; 2016c; Singels *et al*., 2016a; 2016b). Although the current model uses a pre-agricultural Holocene habitat distribution map as a proxy for the interglacial Middle Stone Age, we are also running simulations of different climate states, and shifting ecological patterns in order to simulate foraging during other temporal phases (Marean *et al*., 2015; Shook *et al*., 2015).

The model

The ABM is programmed using the Netlogo toolkit (Wilensky, 1999), and its basic structure has been adapted from a published model based on the hunting patterns of Ache foragers of Paraguay (Janssen and Hill, 2014; 2016). Like the Ache model, the ABM is made up of three entities, each with their own set of behaviours and variables: cells, camps, and foragers (see SOM for a full model description using the ODD+D protocol). The parameterisation of the model has not been copied from the Ache case study.

The 60,000 cells of the ABM's gridded landscape each represent 1 hectare of habitat with one of 14 defined types. Nine are terrestrial ecological types and an additional four are coastal types. Each type is assigned an average caloric return value in kcal/hour units based on our empirical research into available food resources. For the purpose of this paper this includes just shellfish for coastal cells and plant resources for terrestrial cells. Terrestrial mammal hunting is being incorporated into a future iteration of the model and the data currently being compiled.

Mobility decisions are made at two temporal scales represented by the camps and the foragers. Camps represent the collective decision making of the foragers and are used for tracking food sharing and average returns of foragers. The camps select and move to a new location at the beginning of each day as a mobility target for the forgers who are members of that camp. The foragers then spend their day making many fine spatial and temporal scale movements to maximize their individual caloric returns.

A large proportion of the model's code and the variables of the three entities are dedicated to the accounting of foraging time spent and left per day, calories acquired and shared, resources available, those left, and the time until they are replenished (see SOM).

A much smaller part of the code is the mechanism through which the foragers and camps make their mobility decisions with the purpose of maximizing net caloric returns. As there are several complicating factors to be accounted for by this mechanism, outlined above, we shall start simply and build up to the full description of the camp's decision making algorithm (see also Box 1).

Spatial variability

As noted, each cell has a value associated with its return rate (kcal/hour) based on the habitat type. Within a certain perceptual distance, camps assess the different return rates and are able to determine which cells have the largest caloric return for the available hours of foraging time. Since some of these cells are more distant than others, travel time needs to be factored into the mechanism. Often, foraging models will subtract a given amount for the caloric effort required to move (e.g. Lake, 2001). In our model, we focus on a larger factor, which is that the more distant the cell, the more time is spent on travel and thus lost to collecting resources. We therefore subtract the required travel time from the available foraging time in the calculation of net caloric return. Like the marginal value theorem in OFT (Winterhalder and Smith, 1981), the net caloric return after travel to a targeted cell must be greater than the caloric return of the currently occupied cell to justify moving.

Temporal variability

In a recent paper, De Vynck *et al.* (2016a) empirically demonstrated Marean's (2010) hypothesis that coastal shellfish are a calorically valuable resource but only if the tides are favourable. The return rate of shellfish varies with two cycles, firstly a daily high-low cycle of ~12 hours with the highest returns lasting only during the two lowest hours of tide, twice per day. In winter only one low tide is harvestable in daylight, in summer a second low tide might be available during daylight. For simplicity, we assume that shellfish are only harvestable for the first two hours each day, with the rest of the foraging day being spent on nearby terrestrial resources. In a future version of the model, summer's second daily low tide may be included as well.

A second cycle occurs over ~15 days where full and new moons create additional amplitude of tidal height change known as Spring tides. De Vynck *et al.* (2016a) demonstrated that high caloric returns are only available around these Spring tides and only for about

5 days out of every 15 day lunar half-cycle. The ABM cells are updated according to these cycles to reflect the currently available net return rates. Terrestrial plant resources will be similarly updated to reflect seasonal changes when the data has been fully collated (De Vynck *et al*., 2016b, 2016c; Singels *et al*., 2016a, 2016b).

Temporal foresight and time discounting

We noted that travel time is subtracted from available foraging time to arrive at the net caloric return. This could reduce the attractiveness of a high return cell that is at considerable distance. However, the balance of the equation changes if more days of foraging are accounted for. As mentioned, the Spring tide lasts for ~5 five days (or at least for two hours out of each of five days) and subtracting the travel time needs only to occur on the first of those days. We therefore sum the net caloric return over a given number of days of foresight.

It is advantageous to know when the Spring tide *has arrived*, but it is even more advantageous to know when it *will arrive*. This temporal forecasting of a given number of days of foresight has the additional advantage of allowing foragers to arrive as the Spring tide, or other high value resources, becomes available rather than beginning to travel towards it when it arrives and missing the first day or two of high returns. Foragers do not need to be in visual range of the coast to forecast the arrival of the Spring tide. One simple method they may use is to judge by the cycle of lunar phases, another is a more complex calculation involving converting solar days to lunar days. However, the method used is less important than noting that it is possible from far inland.

The final aspect to temporal forecasting to be included is that calories today are comparatively worth more than the same number of calories in the future. This concept, known as time discounting, has been documented in economic contexts (Rogers, 1994) as well as in several ethnographic contexts (Kirby *et al*., 2002; Rosati *et al*., 2007; Salali and Migliano, 2015). Several equations exist for calculating the present value of future resources, but the hyperbolic equation (Eq. 1) has been demonstrated to most closely match experimental data (Kirby *et al*., 2002). The discount rate *k*, that is how steep is the fall-off of value with time, varies experimentally, but tends to range between 0.01 and 0.25. Thus rather than simply summing the resources over several days of foresight, we calculate the present value of future calories according to Eq. 1 before summing them. The primary effect of time discounting in our foraging system is to prevent arriving several days before a resource actually appears (e.g. arriving two days before the Spring tide).

$$V = \frac{A}{(1+kD)} \tag{1}$$

where *V* is the present value of a caloric return *A* after a delay of *D* (in days), and *k* is the discount rate parameter (Kirby *et al*., 2002).

Decision making algorithm summary

In summary, the core mechanism of the Paleoscape ABM is a decision making algorithm whereby camps make a prediction about which cell will maximize net caloric returns for its foragers. The algorithm accounts for spatial and temporal variability in resource availability and is able to weigh the spatial and temporal distance against return rates to make the optimal foraging decision for the group. The foragers, since the temporal scale of their decisions is shorter (i.e. fractions of hours) and their spatial range smaller (moving between one hectare cells and perceiving only a small radius around their current location), use a simplified algorithm without temporal foresight and time discounting. The only temporal variability applied by foragers is the above mentioned limitation of only being able to forage for shellfish during the first two hours of their day.

The above series of factors to be incorporated into a decision making algorithm makes what seems like a very simple task, picking the cell with the highest return, much more complicated. However, by basing our approach on OFT and rolling it into one simple core mechanism, our model attempts to avoid many of the pitfalls of an overly complex and un-analysable model.

Runs and model dynamics

Reporting our analysis of the South African Middle Stone Age foraging system is not the primary purpose of this paper, but a few examples will serve to illustrate the functioning of the model, its decision making algorithm, and its potential for addressing archaeological research questions. It is important to note that the parameterisation of the model (Table S1), and thus all the conclusions below as well, is preliminary as empirical field studies are still underway. Another paper is in preparation that will more fully discuss parameterisation and results of a broader range of model runs.

One of the simplest research questions we have amounts to a detailed account of the carrying capacity. What is the largest viable population size of the South African Cape Floristic Region (CFR) during MIS 5e? This requires not just accounting for consumable resources, but their spatial and temporal distribution, and their sustainability as resources over repeated years of

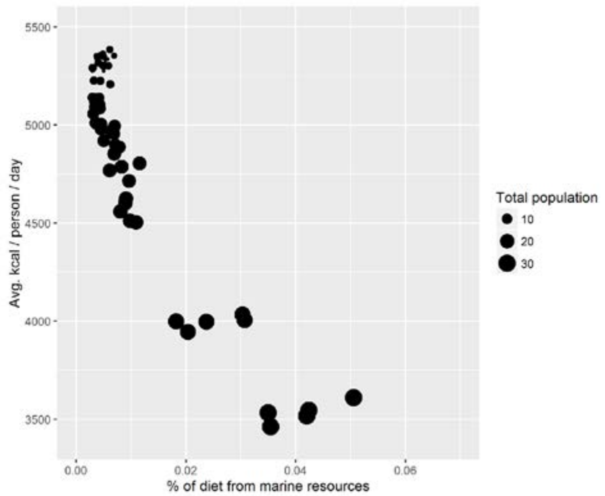


Figure 2. As the population size increases, the average caloric intake of foragers decreases and the proportion of their diet coming from shellfish increases. Foragers are modelled to collect more calories than they personally require (limit set to 5000 kcal/day in these runs) to share with others.

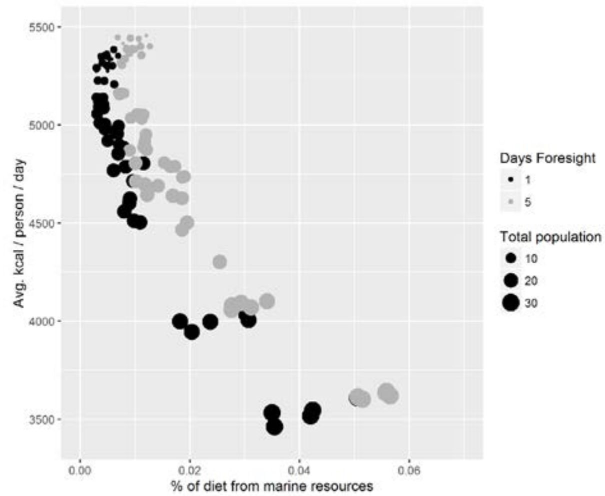


Figure 3. As foragers use temporal foresight to anticipate temporally variable resources like shellfish, they increase the proportion of marine resources in their diet. In these runs, temporal discounting was calculated using k = 0.1.

foraging. By conducting runs of the ABM with different population sizes (Figure 2), we can evaluate the long-term viability of different sized populations and the make-up of their diet. To account for stochasticity, we completed five replicate runs of each population size.

It is unsurprising that the average caloric intake of foragers declines with increased population size. However, it is of interest that the proportion of the diet coming from shellfish tends to increase as the population size increases. This suggests that marine resources could be an important fall-back food either when the population is pushing against the limits of the carrying capacity of the plant resource base, as has been suggested during the Late Stone Age (Marean, 2014), or during short-term decreases in plant food availability (not modelled at present). Marean (2015) has argued that marine resources are a dense and predictable resource. We have shown here that they are also more temporally, if not spatially, abundant since they are replenished on each spring tide (every 15 days), whereas once plant resources are depleted from a given patch they won't regrow until the following year.

We then repeated the above runs of population size variation but with the ability to predict when resources will become available over a period of 5 days (particularly shellfish availability based on tidal cycles).

From Figure 3 we can see that increasing temporal foresight has led to an increase in the proportion of the diet coming from shellfish. For the larger population sizes, when plant resources are becoming depleted across the whole landscape, temporal foresight has also increased the average calorie intake of the population. Beyond just demonstrating that the temporal foresight part of our algorithm works as intended, this may show a tangible caloric benefit of the cognitive capacity previously suggested by Marean (2015).

Discussion

In this paper we have developed an agent-based model of the foraging system of Middle Stone Age coastal South Africa near the archaeological sites of Pinnacle Point, Blombos Cave, and Klasies River Mouth. The ABM is designed around a decision making algorithm based on optimal foraging theory principles and ethnographic observations. The design allows the model to be both rigorously empirically grounded in a large amount of field data specially collected as inputs to the model, and simple enough to be clearly analysable. The core mechanism of our model is both complex enough to capture the multiple factors involved in optimally selecting sub-hourly foraging decisions within a spatially and temporally heterogeneous resource landscape and flexible enough to be applied to multiple archaeological or ethnographic case studies.

The model outputs have been designed to facilitate comparisons to the published faunal records by allowing comparison between simulated and observed archaeological records of frequency of specific shellfish and mammal species.

We also have emphasised the importance of appropriate theory to ground the bottom-up design of ABMs built to test archaeological research questions. While levels of abstraction are required for any modelling (or explanatory) endeavour, some ABMs have not been as rigorously based in theory as they might have been. OFT can provide this basis not just to ABMs with foraging related research questions, but also those focused on the downstream effects of foraging related mobility including: dispersal, population dynamics, inter-group interaction, territoriality, and human-environment interactions. Using this approach has multiple benefits including better comparability among different ABMs, a more systematic basis for the evaluation of model code and results, and comparability to related research in ethnography and ecology.

The decision making algorithm presented here will become more complex as other resources desired by hunter-gatherers are added, such as terrestrial mammal hunting, wood for fuel, raw materials for making tools, fresh water, and ochre for pigment. The present algorithm has established a common currency of calories as a way of making different food resources directly comparable. This approach presents some limitations given some other resources, as well as the physiological requirements for certain proportions of macro-nutrients, are not available in every food resource. Future iterations of the model will address this limitation using established theory from OFT (Hill, 1988).

Although not an initially articulated goal, it is worth noting that the use of this ABM approach within the larger South African Paleoscape research program has led to several new insights and lines of research, as well as novel published work (De Vynck *et al*., 2016a; 2016b; 2016c; Singels *et al*., 2016a; 2016b). For example, the combination of an OFT-based approach and ABM development has helped to redesign plant and shellfish sampling protocols. Initially, sampling was focused on the caloric return rates of different resources. However, ABM development has pointed towards the importance of other variables such as walking speed, search times per habitat, and area observed per linear transect.

Rather than being a separate research project, ABM development has been integrated into the broader research goals of the project. In synthesising works, Premo (2010) and Lake (2010, 2014) have classified archaeological ABMs by two very distinct goals; hypothesis testing and hypothesis generating (a third was for developing quantitative methods but is not relevant here). Here we have been striving towards both goals, but by using a bottom-up approach based in OFT, we are avoiding problems of circular reasoning. The Paleoscape model can both help to test explicit hypotheses derived from archaeological inference, and help to generate new insights and hypotheses to be addressed using archaeological data by observing unexpected or emergent model dynamics.

Conclusion

Janssen and Hill (2014, 2016) demonstrated that an ABM approach that is carefully grounded in optimal foraging theory can closely replicate ethnographically observed foraging returns of a group of hunters. They also demonstrated that social aspects, like the size of cooperative hunting groups were partly the result of optimizing caloric returns while minimizing risk through food sharing.

In this paper we demonstrate that this approach can also be fruitfully applied to the past where direct ethnographic observation is not possible. Here we describe the decision making algorithm and broad design principles of our model. We present some of the possible model outputs such as the expected proportions of different food resources, effects of changing population size, and the effect of future planning on foraging returns. Future work will greatly expand the range of questions to be explored, including questions related to systems of food sharing, formal tests of hypotheses related to Middle and Late Stone Age foraging behaviour, direct comparisons to archaeological assemblage change over time, and predictions of inter-group interaction, territoriality, and defence.

This formalised framework for investigating past human behavioural hypotheses has been laid out in previously published work (Marean *et al*., 2015) and after several years of cooperative research, it is paying off. Palaeoclimate models inform paleo-vegetation distribution models which inform the resource-scapes applied to our ABM (Shook *et al*., 2015). Using this multi-level approach, each grounded in established data, method, and theory we plan to extensively test old hypotheses and generate many new ones.

APPENDIX

Model description

This supplement is a description of our model following the Overview Design Details + Decision (ODD+D) Protocol initially described by Grimm *et al.* (2006, 2010) and later updated by Müller *et al.* (2012) to incorporate human decision making.

This version of the model is used in authors' "An agent-based approach to weighted decision making in the spatially and temporally variable South African Palaeoscape" in 44th Computer Applications and Quantitative Methods in Archaeology Conference (CAA2016), Oslo, Norway.

The model is an adapted version of Janssen and Hill's (2014, 2016) model of the hunting system among Ache hunter–gatherers. Like Janssen and Hill, the current model is explicitly based on principles of Optimal Foraging Theory (for an alternative approach to blending OFT and ABM in a foraging model see Lake, 2000, 2001). The principle difference is that the present model is designed for plant and shellfish harvesting rather than hunting. This leads to a cascade of differences in how mobility decisions are made.

Overview

Purpose

The purpose of this model is to explore the dynamics of a human foraging system including the exploration of decision making rules for camps and foragers. The landscape and food resources relate to the Middle Stone Age of coastal South Africa during an interglacial phase such as MIS 5e. Several specific research questions will be addressed with the model including maximum sustainable population size, role of inter–tidal foraging in the diet and its impact on mobility patterns, and the impact of future planning. In addition, the process of model development is closely linked to complementary research on the impact of climatic and ecological changes on past human populations.

Entities, state variables, and scales

There are three types of entities in the model: cells and two types of agents. Cells each represent one hectare of a foraging landscape. A georeferenced raster map of a section of South Africa is imported with values representing one of 14 terrestrial and coastal habitat types. Each cell is assigned associated variables relating to the caloric return rates of harvesting, time required to harvest, current state of depletion, and time until replenishment based on its type. The total landscape is 60,000 hectares, with a fraction of that representing inaccessible ocean.

The return rates of these coastal cells cycle between two values, one for regular and Neap tides which last for 10 days, and one for Spring tides which last 5 days. The spatial and temporal distribution of resource abundance over the landscape influences the pattern of mobility and the proportions of resources collected.

Like the Ache hunting model, there are two types of agents, namely foragers and camps. Camps may move at the beginning of each day but have a limited mobility range. Camps make mobility decisions designed to maximize caloric returns for the group over a given number of days. Foragers are individual people, each a member of specific camp, who have a time budget in hours that are available each day. Foragers make their own mobility and resource harvesting decisions designed to maximize their caloric returns during the time they have left in their day. Foragers' time budgets are reduced by fractions of hours during harvesting and while walking between cells. Camp and forager variables are used to keep track of time left and kilocalories collected.

Process overview and scheduling

Each time step represents one day. At the beginning of the day, cells and camps are updated. A 15 day tidal cycle advances by one day and if in the last 5 days of this, return rates are updated to reflect Spring tide resource availability even if it had been harvested during the previous 10 days. Depleted terrestrial cells decrease their time until regrowth by one day and if at zero, their return rate is replenished. The camps then use a decision making algorithm to decide on their location for the end of the day. The maximum range of this move is 75% of a day's walk from their previous location but may be a much shorter distance. If the selected cell is within range they will move to it, if it is beyond their range they will move as far as they can in the direction of that cell.

Foragers then begin a loop where they make mobility and harvesting decisions with the time they have left in their day. During each iteration of the loop, foragers in random order estimate the time required to walk directly to their assigned camp. If their time left is greater, they make a mobility decision designed to maximize their daily caloric return. After moving to a cell, they subtract their travel time. They harvest 20% of the resources of that cell, reflecting a linear 100 m transect with 10 m visible on either side, and subtract the time expended in harvesting that resource. We assume that foragers are able to observe a previous forager's transect and thus, the return rate of each cell remains constant until it is completely depleted (Figure S1). If their travel time to camp is less than or equal to their time left, they move one cell towards their camp and do not harvest resources. Foragers repeat this loop until they run out of foraging time. As harvest times are different per habitat, foragers are asynchronous during each day. When all foragers have used up their time and returned to camp average caloric returns are calculated by each camp.

Upon being fully harvested, terrestrial cells set a counter to 365 days. This counter is decreased each day to simulate plant regrowth and as cells reach zero, their resources are replenished. More detailed plant surveys are underway in South Africa and additional details regarding seasonal plant cycles or differing regrowth rates will be incorporated into a future model.

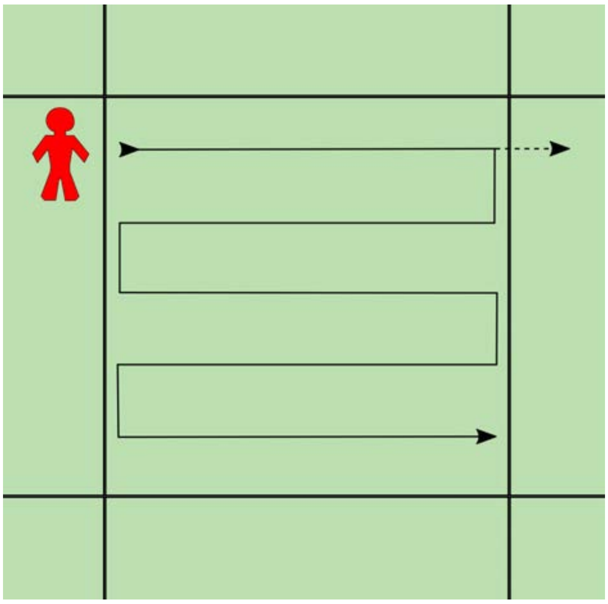


Figure S1. Schematic of a forager agent systematically searching a single cell (solid arrow). By not overlapping the swaths (we assume they are able to recognize previous foragers' harvesting activities) they maintain a constant return rate over five passes across the cell. Alternatively, the forager could decide after the first pass that the neighbouring cell has a higher return rate and move there (dashed arrow). That would leave the cell with the same return rate but 20% less harvestable time available to future foragers.

Design concepts

Theoretical and empirical background

The model design is based on Optimal Foraging Theory (OFT) and implemented according to OFT's definitions of habitats, patches, and prey (Stephens and Krebs, 1986; Janssen and Hill, 2014, 2016). Habitats are geographical regions with consistent characteristics such that a statistically constant pattern of food resources will be encountered. This leads to an average expected return rate for individuals searching that habitat. Patches are smaller units of habitat with a finite number of resources. On the time scale relevant to daily foraging, patches may be depleted as their return rate relative to other patches drops. In our model we assume a systematic search per patch, which means that the return rate per patch remains constant until that cell's resources have been completely exhausted at which point no other resources are available. While our field research has shown that certain plant resources do appear in concentrated clumps only a few meters across, at the scale of a hectare an individual forager has a reasonably consistent return rate given a habitat specific amount of searching and processing time. In the current implementation, there are no prey species.

While the broad framework of the model is based on OFT and ethnographic observations, some model details have been incorporated that are specific to South Africa. For example, water availability has not been included as a constraint on camp location decisions. A paper on this subject is in preparation, but preliminary data suggests that water sources are relatively well distributed across the landscape and therefore would not have been as important a constraint in most habitats as in some other regions (Cowling and Mars, personal communications). We have worked closely with a variety of researchers with knowledge of South African archaeology, ethnography, ecology, botany, and marine biology to ensure the relevant factors are being considered in the decision making framework of camps and foragers.

Individual decision making

Camps and foragers make similar decisions designed to maximize their caloric return given their available time. In each case, the agent assesses individual patches with the assumption that its neighbouring patches will be similar. That is, the return rate of a cell is multiplied by up to several days of foraging time even though that patch may be fully exploited in a fraction of that time. This is a reasonable, though not strictly accurate, heuristic that we use for computational efficiency. This heuristic introduces some uncertainty into the estimated return for camps and foragers since the neighboring cells may not have the same return rate or may be depleted. We assume that camps and foragers have prior experience in this landscape and thus know the condition of cells in the landscape. No partial memory aspect is included. See below for details.

Learning

Camps and foragers do not learn or adapt their decision making strategies in this version of the model.

Individual sensing

In their decision making algorithm, camps use the daily foraging budget, distances to assessed cells, return rate of all cells, and whether a cell is depleted or not. In assessing the return rate, camps also understand the impact of the tidal cycles on return rates, and may forecast the high return Spring tides several days in advance. Although not explicitly modeled, camps are assumed to have global knowledge of current return rates through information exchange and experience.

Foragers keep track of how much time they have left in their day, the distance to their camp and how much time it will take to travel there, how many kilocalories they have collected so far that day, and the current return rate of patches within a specified radius and coastal patches even if they are outside of the radius.

Individual prediction

Although not explicitly modeled, camps and foragers are assumed to have knowledge of the tidally affected coastal return rates through the observation of lunar phases. This also allows camps to anticipate the arrival of the Spring tide. A future version of the model will incorporate data from seasonal plant phenology for predicting the availability of plant resources as well.

Interaction

Camp and forager interaction is indirect as their mobility decisions are affected by other foragers' depletion of resources. However, the location of other foragers and camps are not factored into mobility decisions.

Collectives

Camps consist of a number of foragers who begin their day at the previous day's camp location, and end their day at the new camp site. Average caloric returns are calculated both for individual foragers as well as for camps under an assumption of food sharing. Foragers are assigned a camp on initialization of the model and do not change camps.

Heterogeneity (agents)

Agents are not heterogeneous in their state variables or processes. All agents use the same decision algorithm.

Stochasticity

The order in which camps move, and foragers move and forage, is randomized. Since each forager is indirectly affected by the distribution of available resources, there is a minimal impact of this randomization. In certain rare circumstances, a forager is not able to move to or towards the cell they determine to have the highest net return due to an uninhabitable cell being in the way (such as an ocean). In these cases, foragers move to a randomly selected cell in their immediate 8-cell neighbourhood to help them continue moving.

Observation

Output variables will vary based on the specific research question being evaluated. The model accounts for time spent and calories collected per forager, per camp, and per cell. These may then be aggregated into average caloric returns, days without food, and ratios of different food types (e.g. plant vs marine, or per habitat type). Mobility characteristics such as frequency of camp movement, distance traveled per camp or forager, and time spent in proximity to the coast may also be measured.

Details

Implementation details

The model is implemented in Netlogo 5.3.1 and may be downloaded from the author's CoMSES.net account[1] (Wren, 2016).

Initialization

During the setup procedure, variable settings are read from the user interface to determine which landscape will be used, and how many camps and foragers there will be. Setup assigns return rates and harvesting times to all cells based on their habitat type. Several other accounting variables are set to zero such as calories collected and distance traveled. Additionally, if a number of days of foresight are being used, a temporal multiplier is calculated using the hyperbolic time-discounting formula. All terrestrial cells are set to be full of resources which results in the first year of the simulation being more productive than subsequent years.

[1] https://www.comses.net/codebases/5356/releases/1.0.0/

Input data

Habitat data

The habitat map consists of two data sources. Vector GIS layers of terrestrial habitats were taken from a digital appendix to Mucina and Rutherford (2006) and converted into raster format at one hectare resolution. This pre-agricultural Holocene distribution is used as a proxy for the interglacial Middle Stone Age. Climate and vegetation simulations are underway to model habitats for other climate phases.

The coastline of the study region were walked in order to sample underlying geology. De Vynck *et al.* (2016a) found that shellfish return rates varied consistently with underlying geology and used this as the basis for differentiating returns rates among other variables. We used GPS data from this coastline survey and combined it with the terrestrial data to create a raster model of all habitats at 1 hectare resolution divided into 14 distinct habitat types.

Details of field experiments in coastal shellfish foraging are documented in De Vynck *et al.* (2016a), and in plant foraging in De Vynck *et al.* (2016b, 2016c) with some additional caloric data from Singels *et al.* (2016a, 2016b). Note that the values in the table are estimated given currently available data, but that more rigorous estimates are underway.

Parameter values

Other parameter values are either estimated from ethnographic sources or are actively being derived from fieldwork in South Africa. For example, walking speeds through different habitats are being recorded during the process of plant surveying. The amount of harvesting time available to foragers is estimated from ethnographic sources including Hill's work with Ache foragers of Paraguay (Janssen and Hill, 2014, 2016) and this is consistent with Hadza foragers in nearby Tanzania (Hawkes *et al.*, 1997). One exception to these two sources is the camp mobility distance which is calculated as a percentage of a day's walk (Eq. S3).

Submodels

Here we discuss the details of the forager and camp mobility decisions, the tidal cycle, and including our implementation of forecasting return rates over several days.

Camp decision algorithm

Camps assess all cells then select the cell which has the maximum net caloric return determined by Eq. S1. If the cell is a coastal cell, an adjustment is made as the return rate is different for the two hours of lowest tide at the beginning of the day versus the remaining hours. In this case, the first two hours (minus travel time) are multiplied by the low tide return rate, followed by the remaining hours multiplied by a randomly selected adjacent terrestrial cell (which are generally higher than the high tide return rate).

Available time may also be multiplied over a specified number of days of foresight to reflect future planning. In these cases, the caloric returns of future days are discounted according to a hyperbolic time discounting

Habitat ID	Habitat Name	Return rate (kcal/hr)	Harvest time (hours/ha)
1	Freshwater wetlands	2000	17.9
2	Alluvial vegetation	1160	13.4
3	Strandveld	1200	1.17
4	Saline vegetation	0	0.83
5	Renosterveld	100	0.67
6	Sand Fynbos	1020	0.72
8	Albany Thicket	100	0.65
9	Limestone Fynbos	470	0.70
10	Aeolianite	1450(l)/250(h)	1.5
11	Sandy beach	150(l)/250(h)	1.5
12	TMS Boulders	1100(l)/250(h)	1.5
13	TMS Rocky Headlands	1100(l)/250(h)	1.5
14	TMS Wave Cut Platforms	1100(l)/250(h)	1.5

Table S1. Return rates and harvest times per habitat type. Habitat IDs 10 or more are coastal habitats which have different return rates for the lowest (l) two hours of tide vs. the rest of the day (h).

Figure S2. Screenshot of the Netlogo raster landscape where habitats are colour scaled according to their caloric return rates (lighter shades = higher returns). This view is during a neap tide when coastal returns rates are low (black).

Parameter	Description	Default value	Value range
nragents	Number of foragers per camp	7	1-30
nrcamps	Number of camps	3	1-30
Walk-speed (km/hr)	Speed foragers will walk when not harvesting resources	2	1-5
Camp-mobility	Maximum distance a camp may travel per day	Eq. S3	n/a
Vision-forager (cells)	Distance in hectare cells that a forager sees when making a mobility choice	10	5-75
Vision-camp (cells)	Distance in cells that a camp sees when making a mobility choice (if global-knowledge is off)	50	1-50
Global-knowledge?	Switch to determine if camps have knowledge of all cells, or only ones within the vision-camp radius	True	True/False
Map-zone	Selects the full region or different sub-zones of the study area	z2 (Pinnacle Point)	z1 (Vleesbaai), z2, or full
Max-kcal-collect (kcal)	Maximum number of resources a forager will collect in a day	5000	1000-5000
Days-of-foresight	Number of days camps will forecast return rates over	1	1-5
Discount-rate	k in Eq. S2. Controls the steepness of the fall-off in value with days of foresight	0.1	0.01, 0.1, 0.25

Table S2. Default values and ranges for other parameters used in the model.

formula (Eq. S2). The discount rate parameter (*k*) determines the fall-off rate of value with number of days in the future.

*Net caloric return = ((discounted_return) * hours_per_day – (distance / camp_mobility * hours_per_day * current_return_rate)* (S1)

where *camp_mobility* is defined by Eq. S3 and *discounted_return* represents the summed returns over a defined number of days of foresight (d_f)

$$\text{discounted\_return} = \sum_{D=0}^{d_f} \frac{A}{(1+kD)} \qquad \text{(S2)}$$

where *A* is the caloric return after a delay of *D* (in days), and *k* is the discount rate parameter and

*camp_moblility = daily_time_budget * walk_speed * 10 * 0.75*

which assumes that the maximum distance the camp can move in one day is 75% of a day's constant walking.

Forager decision algorithm

Like camps, foragers assess cells (within a visual range) and select the cell with the maximum net caloric return (Eq. S4). The algorithm similarly subtracts travel time and adjusts for the low and high tides. The only difference is that foragers' available time is based on how much time they have left in their day and no future days are accounted for.

*Net_caloric_return = (current_return_rate * time_left) – (distance * time_walk_cell)* (S3)

where *time_walk_cell* is the time in hours needed to walk 100 m as calculated from the *walk_speed*. (S4)

Lunar tidal cycle and forecasting

The ~15 day lunar cycle has a dramatic effect on the return rates of inter-tidal shellfish availability such that only around the Spring tides, are foragers able to get a sufficiently high caloric return to justify the risk of acquiring the resource. De Vynck *et al*. (2016a) demonstrated that under the best combination of conditions return rates could exceed 3000 kcal/hr. However, waves along this coastline can be powerful and could sweep foragers off slippery rocks into the ocean making the lower return rates during non-Spring tides much less attractive. Our intertidal foraging experiments during different parts of the lunar cycle and under a variety of weather and forager characteristics have led us to determine that only 5 days out of each 15 day cycle have high return rates, with the other 10 being much lower.

A tidal-cycle procedure updates the return rates of coastal cells at the beginning of each model day. If a coastal cell is fully depleted during a non-Spring day, it will be replenished to the full return rate on the first Spring tide day to reflect foraging lower in the inter-tidal zone. If a cell is fully depleted during a Spring tide day, that cell will not be replenished until the beginning of the next Spring tide (i.e. will remain at zero return rate during the 10 days of non-Spring tides). Although this replenishment rate may seem surprising, our fieldwork has demonstrated that inter-tidal return rates are sustainable at this rate (De Vynck, personal communication).

To allow for forecasting return rates over a number of days of foresight, a list of return rates over the 15 day cycle is first established based on whether or not the cell is currently depleted. The position in the list is determined by where on the tidal cycle the current day rests, and then a sublist of based on the number of days of foresight under consideration is extracted. The discounted return formula (eq. S1) is then applied but using the different return rates for Spring tides and non-Spring tides instead of a fixed return rate.

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Teaching Archaeology in the Digital Age

Mieko Matsumoto and Espen Uleberg (eds) 2018. ***CAA2016: Oceans of Data***
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
Oxford: Archaeopress

Archaeological Education for a Digital World: Case Studies from the Contemporary and Historical US

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Abstract

This paper takes as its premises that 1) archaeological education extends beyond the university walls to embrace the needs of a wider public, and 2) archaeology is an integrated discipline that includes the analysis of not only material culture, but also texts and other modes of human expression. The author discusses initiatives to use digital technologies and techniques to 'teach' 'archaeology' in the broadest sense of both words. Examples include using digital archaeological data from DAACS.org to teach analytical processes and the scientific method, the class-sourcing/crowdsourcing of archival transcription using FromThePage.com, and building websites to teach both archaeological content and digital literacies. Much of what some now call the Digital Humanities is not new to archaeology, but we will do well to embrace technological and methodological innovations in the realm of education, just as we have in our research.

Keywords*:* pedagogy, digital technology, historical archaeology

Introduction

There is no question that digital technologies are transforming both archaeology and education. What does it then mean to teach archaeology in a digital world? This paper begins with two key premises: 1) archaeological education extends beyond the university walls to embrace the needs of a wider public; and 2) archaeology is an integrated discipline that includes the analysis of not only material culture, but also texts and other modes of human expression. In other words, *education* is not only about what happens in a classroom for people identified as 'students,' and *archaeology* embraces an extensive range of evidence left by people in the distant, or not-so-distant, past. With this expansive view of archaeological education in mind, three case studies are used to illustrate the ways in which archaeology and digital technology can intersect with pedagogy.

Computer technology is not new for archaeological education. For example, I remember distinctly the simulated excavation software 'Adventures in Fugawiland' that the professor of my Methods in Archaeology course used to supplement our textbooks and lectures, more than 25 years ago. And yet, according to Karsten Lambers and Hans Kamermans (Lambers and Kamermans, 2016), pedagogical themes had not been discussed at a Computer Applications and Quantitative Methods in Archaeology conference for many years, until the recent revival in Siena in 2015. This is in stark contrast to the close link between digitally-enabled research and digital pedagogy that has emerged under the rubric of 'the Digital Humanities' (e.g. Gold, 2012). Why the difference; is it because our research is so bound up with computers, with the digital, that they are taken for granted? Many of our colleagues in literature and art history are only now discovering, for example, the joys of big data and the challenges of visualization. They are just beginning to explore the ways in which the digital turn can transform research. As archaeologists, we may find that it is precisely the pedagogical component that connects a Digital Archaeology to the Digital Humanities, distinguishing it from archaeology-as-usual (Watrall, 2016).

One aspect of digital technology that has already advanced archaeological *research*, as opposed to education, is the way that it makes the primary data of archaeology so readily available, for both accomplished and novice researchers. But these data can be used for teaching as well as research. Learning-by-doing is an incredibly effective and compelling pedagogical strategy (Blum, 2016). This is no surprise for anyone who has ever taught an archaeological field school or laboratory class. We ought to harness digital resources and technologies to infuse *all* of our educational efforts with opportunities for what it is now fashionable to call 'active learning.' Why restrict such a powerful pedagogical tool for use only in specialised 'methods' classes geared towards archaeologists-in-training?

As with a trowel in a field school or a microscope in a laboratory class, novices need extensive guidance to use the digital tools that we deploy in archaeological research. I have found that even digital natives have a lot to learn about the digital world. The good news is that archaeology can be a vehicle for teaching them

digital technology	learners	aims
databases	graduate students and advanced undergraduates	applying archaeological methods, hypothesis development and testing
	beginning undergraduates	learning archaeological methods
internet research and publishing	beginning undergraduates	exploring primary sources, developing research and writing skills
online transcription tools	advanced undergraduates and the general public	exploring primary sources, producing data for analysis

Table 1. Matrix of digital technologies, learners, and pedagogical applications.

skills and knowledge that matter well beyond the narrow world of professional archaeology.

With that orientation to the underlying ideas of the paper, I will now turn to the three examples from my own teaching. Each involves a different data set, a different set of learners, and different aims; each of which must be taken into account when teaching archaeology in the digital age (see Table 1). First, I will briefly compare each example in terms of digital technologies and general learning goals. I will then turn to a detailed comparison of the interactions learners have with these technologies. I conclude with a qualitative discussion of the pedagogical outcomes that learners and archaeologists might anticipate experiencing in the wider digital world.

The digital technologies

The digital technologies that archaeologists employ are many and varied. Some have little application in teaching scenarios beyond instruction that is designed to meet the needs of archaeologists-in-training. Here, I briefly describe the digital technologies and data that I use in both research *and* teaching, before turning to a discussion of how these digital materials can be used for specific educational ends.

The first example uses the Digital Archaeological Archive of Comparative Slavery (DAACS), an online database of information from (at the time of writing) 72 individual slave quarter sites at 32 plantations throughout the US southeast and the Caribbean.[1] It provides downloadable data for comparative analyses to anyone with an Internet connection. It also promotes a set of standards for data recording and especially artefact cataloguing. I use these data extensively in my own research, and several sites where I have excavated are included in the Archive. More to the point, I use data from DAACS to illustrate archaeological concepts and techniques in my classes, and as raw material for projects executed by the students themselves. Their level of expertise has ranged from graduate students specialising in the archaeology of the African diaspora to undergraduates enrolled in a general education course to fulfil their laboratory science requirement (for more, see Agbe-Davies *et al.*, 2014). The shared aim across these populations is to create scenarios in which students can apply the methods they have been learning about in the course, compare their own findings with those that they encounter in their assigned readings, and confront the vagaries of real — as opposed to simulated — data.

In the second case, students in my research seminar for first year undergraduates use and create web resources for learning about life in 20th century black Chicago; specifically at the site of the Phyllis Wheatley Home for Girls, where I conducted archaeological excavations from 2006 to 2009. The aim of these seminars is to "offer an introduction to the intellectual life of the university and focus on how scholars pose problems, discover truths, resolve controversies, and evaluate knowledge".[2] In the class, students use primary data — both archival and archaeological — to produce different genres of electronic texts, including webpages, wikis, timelines, and data visualizations. These activities also provide an opportunity for them to evaluate information that they find online as well as how to cite and give credit appropriately.

The final case involves crowdsourcing the transcription of archival texts, which has so far been piloted to a 'crowd' of students in my classes, but is ultimately intended for the Internet at large. The data come from a collection of store account books archived at my university (Cameron Family Papers, 1757–1978) and pertaining to a nearby plantation called Stagville,[3] where I have begun archaeological investigations. Recently, my efforts have been aimed toward developing a tool for online transcription of these records that opens the process up to a wide audience. FromThePage is a tool that until recently was designed for the crowdsourced transcription of texts such as

1 www.daacs.org

2 http://fys.unc.edu/
3 www.stagville.org

diaries and letters (Brumfield and Agbe-Davies, 2015). It serves up the manuscripts online and facilitates the editorial process.[4]

Learners meet applications

Archaeology as data

Teaching with the DAACS database, the greatest challenges are not archaeological, but technological and general. By the time activities and assignments are introduced, we have usually spent several weeks learning about, for example, frequency seriation (Dethlefsen and Deetz, 1966), mean ceramic dates (South, 1978), and Harrington histograms of pipe-bore sizes (Harrington, 1954). The students have heard lectures on the techniques and read research reports or articles which use the techniques to interpret archaeological sites. Rather than stopping here, students next have the opportunity to apply these techniques to see how/if/when they can be used in testing an archaeological hypothesis. Thus, a hands-on teaching strategy need not depend on the physical presence of actual artefact assemblages.

One benefit of working with data from the archive is the access one has to many more samples than one could expect to provide from one's own excavation materials or curation facility. And there are fewer curatorial concerns. It is not possible for a novice to accidentally separate artefacts from their correct archaeological context; one can set up 'collections' with greater ease and speed than is possible with physical collections. The benefit that I find most pedagogically compelling, though, is that one can concentrate on bigger-picture methodological topics without having to assume (or develop) fundamental skills like identifying artefacts and interpreting stratigraphy. Even people who cannot distinguish among fragments of earthenware, stoneware, and porcelain can still create tables comparing proportions of these categories and, with some knowledge of their different uses, develop interpretations based on their findings. Of course, when it is possible for students to mainline data in this way, it makes sense to impose a tightly-structured scaffolding of assignments to ensure that they do not become overwhelmed. Many students need significant guidance on how to translate an understanding of principles into the application of those principles to actual data.

For general education science students, I gave tightly-structured laboratory assignments with specific instructions on what patterns to look for and how to analyse them. For example, I provided them with pre-downloaded pipe-bore data for them to compare with J.C. Harrington's classic histograms and then to insert into Lewis Binford's dating formula. Upper-division archaeology and anthropology majors have much more latitude to select their own datasets and problems. However, they are required to draft several research proposals and submit draft tables, charts, or visualizations for assessment before they begin their projects in earnest. This process ensures that they get frequent feedback on their ideas, while still having significant opportunities for creativity.

For both generalist and specialist undergraduates, spreadsheet techniques in Excel — the program which dominates the U.S. market — were unfamiliar to many students. These digital natives were tough to wean from their smart phone calculators and convince that it was simpler and less error-prone to use the tools embedded in the very tables that contained their downloaded data, instead of calculating totals, averages, and percentages by hand.

So the key challenge for teaching both groups was to prevent the digital technology — for example, the steps of the downloading process, or unfamiliarity with spreadsheets — from getting in the way of learning about the scientific method and about archaeology. For true novices, this meant providing limited assignments and detailed step-by-step instructions. For undergraduates in upper level classes, this meant significant individualised feedback specific to each person's project. The latter kind of pedagogy is difficult to scale up and use with large classes.

Archaeology and media literacy

In my First Year Seminar, students use (and create) both primary and secondary sources in a digital format. For example, students used library technology to search for and download articles from the *Chicago Defender*, a major newspaper that published stories and announcements about the Phyllis Wheatley Home for Girls. They then used SharePoint to enter information about the content of those articles into a database, recording, for instance, whether a story referred to the residents of the Home or the women who sponsored it, or if it included an appeal for donations to fund the Home's work. Later groups of students used these same articles to create a timeline of events associated with the Home using a web tool called TimeMapper.[5] Another group used the text analysis software MAXQDA to analyse the 'Women's Page' of the *Defender* to understand social expectations for African American women in the mid-1920s. Similar efforts to identify cultural patterns focused on oral history interviews, analysed using the web tool Voyant.[6] Throughout, moving back and forth

[4] http://fromthepage.com/

[5] http://timemapper.okfnlabs.org/

[6] http://voyant-tools.org

Figure 1. Fragments of Pepsi bottles from the Phyllis Wheatley Home for Girls, Chicago.

between genres — in terms of both the sources and the assignments they complete — provokes students to think about 'media' in new ways.

Such activities teach them about how archaeologists and other researchers use the primary archival record to produce and present new knowledge about the past. On the artefact side, members of the class have produced qualitative as well as quantitative studies. For several terms running, each student would be assigned an artefact, such as one of the fragments of Pepsi bottles shown in Figure 1, and then tasked with tracking down information about it for publication to our class wiki. In such an instance, the student would find out about the manufacture of the object itself (what technologies were used to shape and label the bottle?), as well as its uses (how was soda produced and consumed in the early 20th century?), and specific relevance to the site (what does evidence of 'soft drinks' mean when recovered from a Home dedicated to instilling good, Christian influences in its residents?). As we go, we discuss sources of archaeological information on the Internet and how one might distinguish reputable sources from dubious ones. In other years, students created content for the class wiki by analysing assemblages of artefacts, identifying minimum numbers of vessels for example, or comparing artefact distributions for different areas of the site.

In all of these activities, students create pretty good content. Some of course do the bare minimum, but every year I am impressed by the lengths to which some students will go in pursuit of information about an artefact's manufacturer, or in an attempt to find every last mending piece of a fragmented vessel. I also appreciate the students' creativity in organising ideas and designing the final product when freed from the linear structure of a 'paper.' These kinds of assignments are much more interesting to read and grade than a standard 5-paragraph essay or a research paper based on secondary sources. Students respond enthusiastically to the idea that they are not just telling the professor something she already knows, but are in fact producing new knowledge for the group, the professor, future researchers, and other stakeholders, including the current owner of the Home.[7] In tracking down data and presenting the results of their analyses, students are developing digital literacies, even as they learn to 'read' material culture.

Archaeology and the crowd

Archaeologists, because our research is so labour-intensive, likely need little convincing of the value of crowdsourcing.[8] Crowdsourcing is not only an effective means of getting work done — for example compiling a regional database of projectile points (White and Agbe-Davies, 2016) — it is also an effective pedagogical tool (Smith, 2014). It teaches users about the primary material being studied and about the methods used to analyse such material. For the last two years I have been experimenting with having students in my classes transcribe 19th century manuscripts, specifically, account books from plantation stores in operation before and after the U.S. Civil War. The students are merely the first wave of the 'crowd' as my intention is to open the process up online to the wider public as is being done so successfully by large institutions such as the Smithsonian,[9] but also by smaller research groups such as the Colored Conventions Project.[10]

In the case of the transcription activities, the challenges that learners face are material-specific; primarily the difficulty of reading handwritten 19th century texts with unfamiliar abbreviations, vocabulary, and accounting conventions. The strangeness of the texts highlights their material qualities. The fact that they cannot be readily understood forces users to think about them as constructions rather than direct and transparent representations of some past truth. And so, learners need guidance in how to analyse and extract meaning from texts as surely as they do with artefacts.

With these challenges in mind, at first I wanted the digital technology to be as low-effort as possible. Google spreadsheets work (up to a point). With columns and rows, they mimic the structural organisation of an account book. For a collaborative project, the

[7] The field project was developed collaboratively with the Home's current owner (Agbe-Davies, 2010).

[8] One of the term's originators describes crowdsourcing as 'the act of a company or institution taking a function once performed by employees and outsourcing it to an undefined (and generally large) network of people in the form of an open call. The crucial prerequisite is the use of the open call format and the large network of potential laborers' (Howe, 2006).

[9] https://transcription.si.edu/

[10] http://coloredconventions.org/

sheets have the added benefit of being easily sharable. Because the sheets are used only for transcription and not quantitative analysis, technical facility with spreadsheets — other than navigation within one — is irrelevant.

However, as the project expands beyond students in my classes to a larger audience of learners, the materiality of the texts becomes a different kind of issue. Physically housed in an archive, the potential size of the crowd would be limited to those who could go to the texts. A solution to this problem is the web tool FromThePage. It has a steeper learning curve. The user renders the text using simple wiki mark-up (which makes it a compromise between the clunkiness of a spreadsheet and the complexity of TEI[11] encoding). However, it allows the transcriber to render the text in a way that more closely resembles the original manuscript, and enables mark-up that can be used in later analysis. Users may also download content (their own transcriptions and others') for their own use.

In addition to producing valuable data, engaging novices in the transcription of archival texts yields other, pedagogical, benefits. The transcription process engenders close readings of the material, revealing nuances that are easily missed when working with pre-prepared transcripts. Transcription also gives learners a window onto the transformations that occur in pursuit of knowledge about the past: how observations of primary sources become data on their way to becoming evidence in arguments about the past; as well as the role of researchers in those transformations.

Conclusion: why does a digital archaeology pedagogy matter?

Part of the challenge for teaching archaeology in the digital age is to think creatively and critically about *what a given digital technology is good for.* DAACS, for example, offers an extensive data set with which students can learn to set up, and pursue the answers to, research questions. It also serves as a model for developing data structures of one's own. In the case of my First Year Seminar students, MAXQDA is an extraordinarily powerful text analysis tool, but over time it became clear that it is not well-suited to group work, nor is it good for students who are still trying to learn basic social science concepts or arguments. Voyant is more suited to their abilities, aims, and inclinations. And I have already discussed the relative merits of using Google spreadsheets vs. FromThePage for the transcription of manuscript account books. As we all know, just because something is digital, doesn't make it better. Digital technologies, just like archaeological methods, need to be suited to the task at hand.

Likewise, we as archaeologists need to have deliberate conversations about the point of teaching archaeology. In other words, *what is archaeology good for*? What do we expect people to learn and why? What is the place of archaeology in a 21st century university curriculum, or in a 21st century society (Little and Shackel, 2007)? For university students who may not become archaeologists themselves, does the field have a higher purpose than merely broadening their experience?

It could be, simply, that 'archaeology' is the hook that gets students to learn important 21st century skills like generating and using statistical data, writing clearly, and critically analysing social systems. Developing a testable hypothesis was a major challenge for many of my students. Several seniors confessed that they had never been asked to think in this way in their entire college careers. I would be surprised if more than one or two of the students in my most recent class for advanced undergraduates went on to graduate school in archaeology, let alone took up archaeology as a profession, but each of them has now learned how to structure an argument, identify primary data with which to test that thesis, and discuss his or her results.

We could think even more broadly. Maybe the point of teaching archaeology in the digital era is to undermine naïve ideologies of progress, modernity, and the naturalness of consumerism. Archaeology introduces people to bygone ways of being-in-the-world and shows us the roots of our own present. Such perspectives could go a long way towards helping creative people to imagine alternatives to the social challenges they see around them. Or perhaps teaching people about archaeology aims to preserve the archaeological record. We want the woman on the street to know some of the things archaeologists have discovered about the human past so that when she has the opportunity to purchase looted artefacts, she walks away. Digital tools have been deployed in both of these projects. They represent important goals, and there are others we could discuss (see e.g. Dawdy, 2009, and responses).

We could be parochial about it and ask ourselves, how do digital technologies advance archaeology by *better training the next generation of practitioners?* I would argue that we can't replace field or laboratory experiences with simulations. Furthermore, effort should not emphasise training digital natives in the use of a suite of digital tools, but training them in *archaeology* so that they are able to see the application of these tools to their own (perhaps newly-conceived) archaeological ends. Digital technologies give us a reason to ponder which elements of our practice are essential and which

[11] The Text Encoding Initiative (TEI) is 'a consortium which collectively develops and maintains a standard for the representation of texts in digital form' (http://www.tei-c.org/index.xml).

are legacies of the traditional, pre-digital era, practices we could dispense with and perhaps replace with more efficient or effective ones. Should 3D reconstructions of excavation units replace hand-drawn plans and sections? Set in our ways, as humans tend to be, we might not see the benefit of a shift. I for one have lingering scepticism about the benefits of born-digital field recording. However, the archaeologist-in-training who comes into the field when such techniques are part of the collective toolkit, if she is adequately trained in *the point of* recording depositional data, may have all kinds of new ideas about *how* to do it.

Although many archaeologists work in university settings, not all archaeological teaching is directed at university students. Digital technologies can be used to support pedagogy out in the world as well as inside the classroom, and are certainly not restricted to the digital presentation of archaeological content. Archaeological teaching includes creating learning experiences using digital archaeological data. It can also mean opportunities for retrieving, manipulating, and creating digital media. Archaeological pedagogy can open the discipline up to the crowd, providing access to new primary sources and the tools to make use of them. It should be clear that, even when teaching the specific kind of learner known as a university student, we should be open to the possibility that 'archaeology' may not always be the most important thing that we are teaching. It is this expansive view of what it means to teach archaeology that will enable the discipline to thrive in an increasingly digital world.

Acknowledgements

Many thanks to Karsten Lambers and Hans Kamermans for the invitation to participate in the session 'Teaching archaeology in the digital age', and to the other participants in the session for a lively and eye-opening discussion. I am grateful for the insights of Sara DePasquale, Lisa Fischer, and Danielle Spurlock, and three anonymous reviewers whose comments improved the paper substantially.

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Mieko Matsumoto and Espen Uleberg (eds) 2018. ***CAA2016: Oceans of Data***
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
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Teaching Archaeology or Teaching Digital Archaeology: Do We Have to Choose?

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Abstract

In 2011, the French National Institute for Preventive Archaeological Research launched an important programme to promote the use of GIS among archaeologists. This project initiated an ambitious training programme which marks the beginning of the deliberate use of new digital technologies within the Institute. Three training modules dedicated to the use of GIS are currently offered and others are being put forward. The content of training is defined according to the changing practices of archaeologists in preventive archaeology. Considering the fact that most of the archaeologists in the Institute are non-digital native users, training has to be adapted. However, the real challenge is not to lose the real substance of field archaeology. The increasing use of digital technology must not be an excuse for avoiding the basics of archaeology, such as field recording.

Keywords: preventive archaeology, training, GIS, digital technology, field recording

Introduction

Until the end of the 1980s, the archaeology of French national territory was essentially undertaken by non-professionals. However, with the increase of big planning projects such as highways, high speed railway lines etc., archaeologists founded the Association for National Archaeology (AFAN) in 1973 (Talon, Bellan, 2009). The AFAN was a mediate agency under the supervision of the Ministry of Culture (Demoule, 2011). In 2001, on the request of archaeologists, the association became a public institution currently known as the National Institute for Preventive Archaeological Research (INRAP). 'Preventive archaeology' replaced the previous 'rescue archaeology' fully integrated in the planning process. The current organisation of French preventive archaeology has resulted from both adjustments in the law and the construction of professional archaeology by the archaeologists themselves (Talon and Bellan, 2009; Pot, 2009).

Under the supervision of the Ministry of Culture and the Ministry of Research, the French Institute for Preventive Archaeological Research has three missions to fulfil: it detects the archaeological heritage threatened by development and infrastructural work; it studies the data collected and shares the research results within the scientific community and the general public (Pot, 2009). The AFAN was previously the only operator in preventive archaeology. Since 2003, the Institute was henceforth submitted to competitive context (Demoule, 2011). In 1988, 750 archaeologists worked for the AFAN (Gruel *et al.*, 1988). Nowadays, the Institute is comprised of around 1500 archaeologists working in forty-nine centres spread over the national territory and overseas territories. They carry out over two thousand operations a year (85% of trial trenching and 15% of excavations). In 2011, the Institute began to promote and develop the use of GIS as a tool for archaeologists and their daily work. This project initiated an ambitious training programme which has marked the beginning of the deliberate use of new digital technologies within the Institute.

The population of the Institute is characterised by a variety of skills, origins, curricula, careers, etc., all coming from different causes. Due to INRAP's history, the population currently working for the Institute is partly comprised of the AFAN archaeologists from the 1990s and other people integrated year by year. However, the population is no longer young and the first archaeologists of the AFAN will soon retire. Depending on the date of recruitment, the level of archaeological education and practice is very different from one archaeologist to another. In the 1980s, due to the pressure of the planning process and the urgency of excavating future planning projects (Talon and Bellan, 2009), some of the archaeologists involved became professionals without having completed their academic studies (Gruel *et al.*, 1988). Nowadays, the competitive context associated to the economic crisis and the reduction of planning projects makes the conditions of employment harder: the young archaeologists recently employed are sometimes over-qualified for the tasks they are responsible for. However, they are not always *better* qualified or better experienced. It depends on their academic curricula. In short, there is a great difference in background knowledge concerning general practices and use of digital technology between archaeologists. However, the major part of the population of the Institute can be described as a non-digital native population according to the Prensky dichotomy (Prensky, 2001) mentioned in a previous paper by Dutch colleagues (Visser *et al*., 2016).

The aim of this paper is to introduce the continuing education programme of the Institute, showing that it is a part of a complete consideration of the evolution of the job. Indeed, the definition of a training programme cannot be dissociated from a definition of the job itself. As a consequence, INRAP's continuing education programme has been defined according to the main choices of the Institute concerning the evolution of practices. This includes the use of new technologies and the needs of archaeologists concerning methods, techniques and digital archaeology. The global issue of initial training in archaeology in France will be raised in order to propose some thinking matter. According to the topic of the conference, only the training programme related to the use of digital technologies will be discussed in this paper[1]. The point of view is that of the employer responsible for the achievement of INRAP's missions.

French initial training in archaeology: items of discussion

In France, initial training in archaeology is exclusively dedicated to universities. From the end of the 1980s to the end of the 1990s, previous specific training depended on proposed curricula from universities, combining academic knowledge and field practice. One of these was called 'Master of sciences and techniques'[2] and was dedicated to preventive archaeology. It proposed a curriculum focusing on the methods and techniques of archaeology including a substantial part of field practice such as topographic survey, digging, buildings' archaeology *etc.* This practical part of training was associated with a more academic teaching focusing on historical knowledge. Only a limited number of students per year could attend the training which ended towards the end of the 1990s with the Licence — Master — Doctorate reform of the French universities.

[1] The whole training programme of INRAP involves training in the techniques and earthwork technology, management of the technical side of an operation, and the use of mechanical appliances. This part of the training programme shows how the job has changed the last decades.

[2] The M.S.T (*Maîtrise des Sciences et Techniques*) was a two-year long training, from licence (third year of academic curricula) to master.

Firstly, as far as we can tell, current educative programmes are quite heterogeneous, depending on the teachers themselves and the policy of institutions[3]. Universities have attractive programmes to offer students in order to justify their existence. As a consequence, it seems that the part of the programmes dedicated to digital technology or computing archaeology is increasing in order to try to make the curricula suitable for the new digital practices. This does not mean that academic education programmes are suitable for the reality of current practice in preventive archaeology, even digital.

The second point is related to (digital) field recording, which should be one of the fundamentals of archaeology. A 10-year old academic study has made a state of the art analysis on this matter (Desachy, 2008). In France, the stratigraphic recording of the 1970's (Harris, 1989; Barker, 1977) has not been totally accepted and used. Three approaches have been used during the last forty years: the micro spatial analysis or ethnographic approach focused on the artefact; the macro spatial analysis focused on the wide area with or without a small stratification; and the last one, focusing on substantial anthropological stratifications (Desachy, 2008). If archaeologists accept the three approaches as complementary methodological tools, the kind of digging still defines the way of recording (Desachy, 2008). In short, it seems that in spite of the use of common vocabulary, the underlying concepts might be different from one archaeologist to another. As a consequence, a real fear is that the field recording systems currently used are probably not interoperable (Rodier, 2016). Of course, this allegation is not valid for all. Furthermore, it is hard to demonstrate because it is believed that field recording is no longer a matter of discussion. It is supposed to be the basic skill of every archaeologist working in the field, but who is training the current students in field recording today? What parts of academic programmes are dedicated to the basic methods and techniques in archaeology, digital or not? That is unknown. This part of initial training is rarely stressed or detailed by universities.

Due to the variety of existing academic training, it is rather hard to synthesize the main lines of French initial training in archaeology. However, as an employer of archaeologists who come from different universities, INRAP has to consider the skills of each individual in order to be able to offer a suitable further education programme. The broader use of new digital technologies again stresses the lack of consultation between the participants in French archaeology. There is still no general discussion between universities and professionals in preventive archaeology on the

[3] The following universities websites have been consulted to prepare this paper: Lyon III, Franche-Comté, Paris Panthéon–Sorbonne, Tours, Strasbourg, Bordeaux-Montaigne.

definition of the initial training programme and more generally on the definition of the job. As a consequence, the risk of gaps between initial education programmes and the reality of practice is getting larger.

Professionalization of archaeology and division of the tasks

Since the growth of preventive archaeology in the 1980s, archaeologists have defined a division of the tasks. This division is still operative and gave birth to the current job descriptions, which are mainly divided into:

- topographers dedicated to topographic survey of archaeological remains;
- archaeologists responsible for archaeological operations and all the connected tasks such as field recording, exploitation of data, and writing of the final report;
- archaeologists in charge of drawings and cartographic production (graphic designers).

At that point in time, some fields were recognised: archaeozoology, anthropology, carpology, ceramology *etc.* Nowadays, according to the Institute General Direction no less than fourteen different fields are admitted.

Several points linked to this division of tasks can be stressed:

- this division was a necessity due to the context of flourishing projects and the need of efficiency increasing with the competitive context,
- gradually, this division of the work led to a cutting of the whole field process,
- and following this, the emergence of an over-specialisation of the tasks (Ferdière, 2016).

In a way, the development of micro-computing during the last fifteen years enlarged the gap between tasks and people. Before the development of GIS, each task was associated to dedicated software: topographers were associated with AutoCAD, while people working on cartography were associated with Adobe Illustrator. Archaeologists could use both drawing software like Adobe Illustrator and software for databases, with a majority using FileMaker Pro.

Initially, people were not necessarily trained for the tasks they had to do in the field. Gradually, tasks, software and training were mixed. As a consequence, the previous training programme of the Institute for archaeologists mainly focused on software manipulation and not necessarily on the task itself or on the mastering of the basic knowledge. The training sessions were all managed by external service providers and a few of them were conducted by archaeologists.

Ongoing training programme

In 2011, the Institute launched an important programme to promote GIS among archaeologists to systematise their use (Rodier *et al*., 2013). The project was based on two important choices: first, it was decided to systematise the use of GIS at the scale of the archaeological operation (Moreau, 2016). Secondly, the Institute decided to train archaeologists — including topographers, specialists, graphic designers — in the use of GIS and not to delegate this part of the process to specialists. As a consequence, archaeologists have had to adopt and master the tool and the relative concepts. For this purpose, means have been engaged for the definition of further education programmes. Three different modules of training dedicated to the use of GIS (two levels) and statistics (one level) are currently offered.

For each module of training, a working group, gathering members of the Scientific and Technical Direction (for the global and strategic point of view) and people working on the field (for the local and practical point of view) is formed. This group defines the contents of the training. For example, considering a new digital device, the working group decides whether the skills required have to be those of archaeologist or not. In the case of the first option, a definition of a new training including the definition of the goals and the targeted public is done. The definition of training programmes is preceded by experimentation in the field, conducted locally, to test the relevance of the device in the process. In the case of the second option, external providers or experts can be solicited.

The first level ('level 1 GIS') of training is related to the use of GIS in a preventive archaeological process at the scale of the operation. Teaching is focused on collecting, interrogating and representing primary data. It is a three-day training period for all the people working in the field whatever their official mission. This is the key level, required, and not restricted to a specific population. QGIS is the software chosen to train archaeologists. This training is based on the principle of a free division of the tasks among the team's members of an operation. No fixed borders between the tasks are defined; the management of the GIS during the operation is the concern of the team. For example, the digitalization of data can be partly done by the topographer, the graphic designer and/or the archaeologist. The team has to organise the process according to the general conditions of the operation, the availability of the topographer, the wish and the skills of the team's members, etc.

training	duration (days)	target public	software
Level 1 GIS	3	all	QGIS
Statistics 1	5	all	OpenOffice Calc, R, QGIS
Illustrations	4	all doing illustrations	QGIS

Table 1. The first three modules of training linked to the development of GIS.

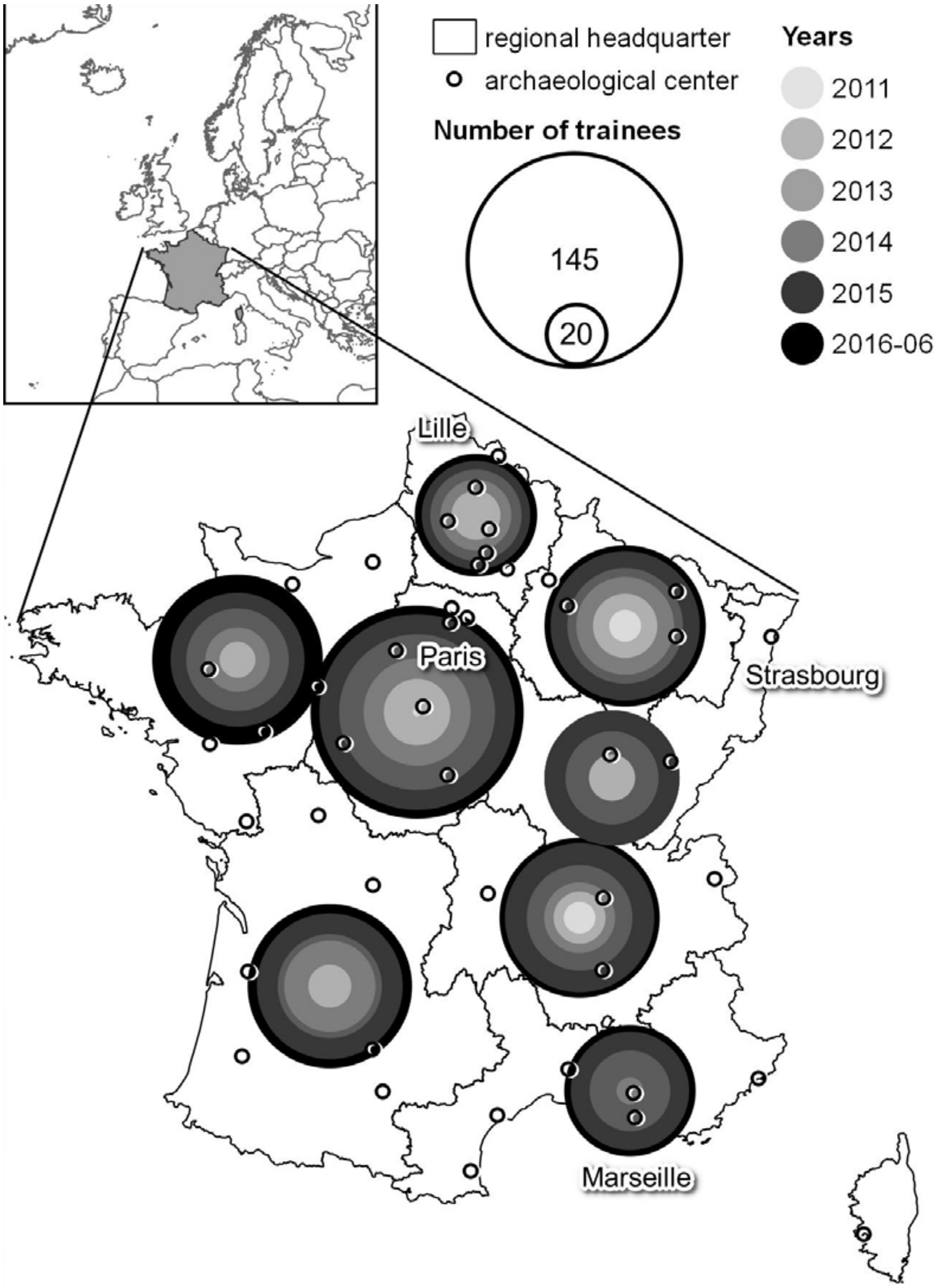

Figure 1. Distribution of the number of trainees by headquarter* from 2011 to June 2016.

* The French National Institute for Preventive Archaeological Research is organised in 8 headquarters as described in a previous paper of the CAA Conferences (Moreau, 2016).

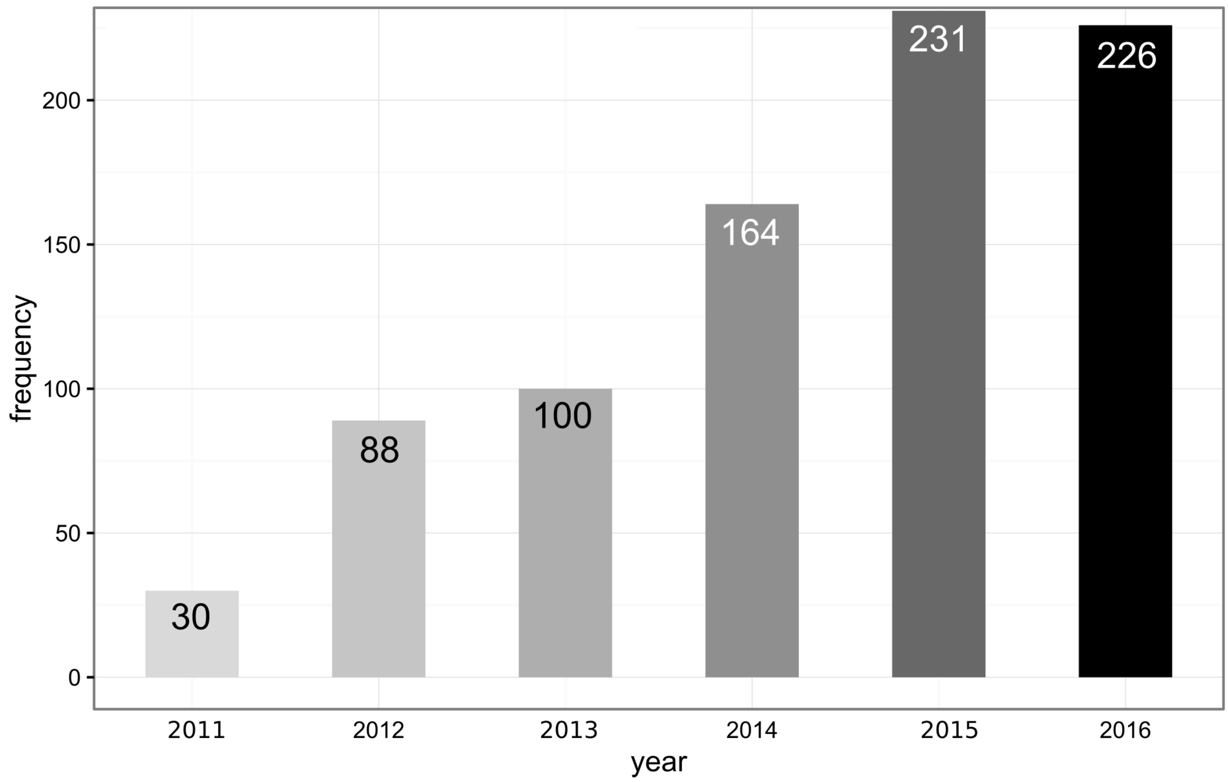

Table 2. Number of trainees from 2011 to 2016 (statistics on the first of October 2016).

Two complementary modules of training are offered. One is dedicated to the manipulation of cartographic data in order to produce the illustrations for the final report. This four-day long training includes an introduction to the semiology of graphics and the mastery of QGIS to produce the main illustrations for the report. This training is offered to people charged regularly or occasionally with the illustrations production. The first two modules of training described above allow archaeologists to reach autonomy in the use of GIS applied to preventive archaeology.

The third module focuses on statistics: it is an introduction to descriptive univariate statistics including the manipulation of data with a spreadsheet and the cartographic representation of quantitative data with QGIS. It is comprised of an introduction to the open-source R software. The goal is to train archaeologists in the basic tools to describe and manipulate simple statistical series. It is a five-day training period for all the volunteers (Table 1).

Two other training modules are soon to be offered. The first will be dedicated to the topographers of the Institute. This forthcoming training session aims at improving the process between spatial acquisition of data on the field and the implementation in GIS software. The second session will focus on data analysis and spatial analysis. It is there an improvement of the first level, in which data analysis is briefly evoked.

Finally, training focused on photogrammetry (used more and more as a complement of the traditional field recording and topographic survey) is about to be organised. Two aspects are treated in the training: the shooting in the field and the exploitation of the pictures in order to produce ortho- photographies, DTMs, and three-dimensional models.

Currently, the training in digital technologies is done in a very classical way: people are gathered in a place for three, four or five days, listening to a teacher and practising at the same time. The teachers are the archaeologists of the Institute, most of whom are the trainees from the earlier courses. No digital training supports have been done yet, except the written tutorials have been done by us; a website specially dedicated to the training provided by the Institute is to be proposed. The reasons for the traditional manner of teaching can be explained as follows: gathering people and working in the same place leads them to debate about their changing methods and habits. In addition, as said before, the population of the Institute is partly unfamiliar with digital tools and it is firstly necessary to work in a familiar way.

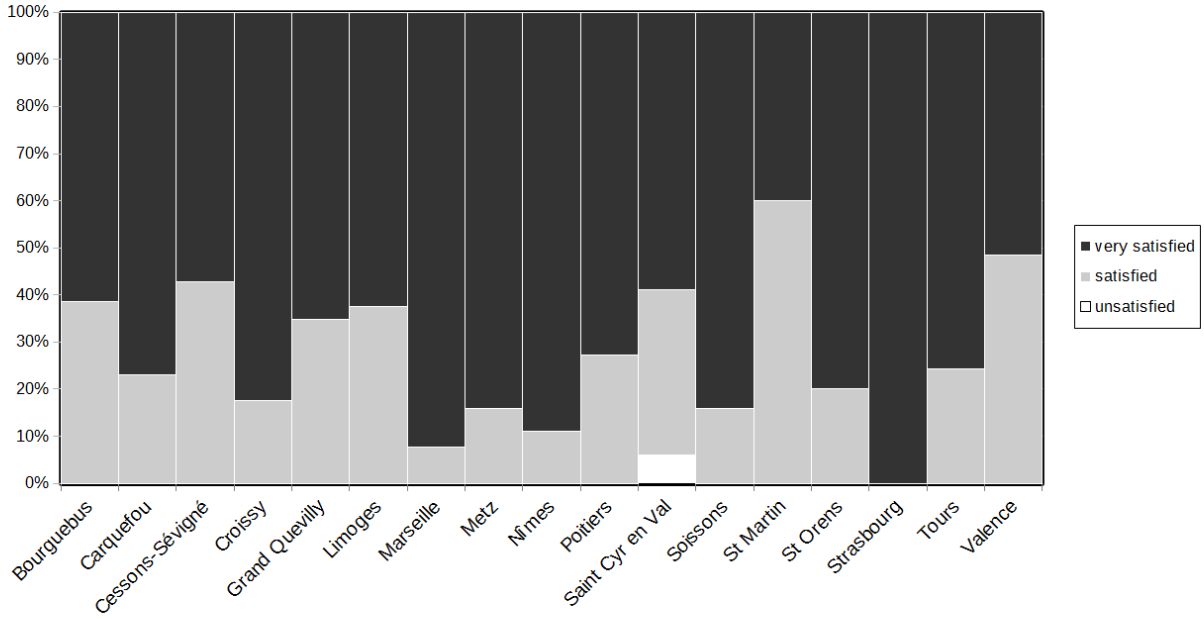

Table 3. Overall satisfaction rate per centre (January–September 2016).

Statistical report

In total, 75 sessions of the first GIS level ('Level 1 GIS') have been carried out since 2011. More than 750 archaeologists have been trained in five years. It represents 45% of all the archaeologists of the Institute (Table 2). The number of training sessions is increasing annually due to more and more demands.

The spatial dispersion of the number of trainees since 2012 shows the progress of the training and the whole project (Figure 1).

Basic statistics have been used for assessing the overall satisfaction of trainees by using their own evaluations. The results presented below highlight the general high level of satisfaction. Considering the fact that nothing is imposed and that people are not obliged to follow the sessions and using the GIS, the results are encouraging (Table 3).

Conclusion

The success of our training reveals the need for archaeologists to be guided into the acquisition of new skills; but not any skills. The definition of training is not dissociated from a reflexion about the changing nature of the job. We train archaeologists in the new skills of the digital age. This doesn't mean that we expect archaeologists to master every step of every possible device used. The increasing number of new digital tools should lead archaeologists into adopting a collaborative behaviour. Concerning the use of photogrammetry, for example, archaeologists have to control the acquisition of the photos on the field without necessarily taking charge of the pictures processing with dedicated software. This part of the process could be realised with the help of a well-trained technician. In a slightly different way, using a GIS is a way for archaeologists to master and explore archaeological data even if some of the related tasks are divided among the member of the team. That is why it is essential for archaeologists to be trained in the use of GIS.

INRAP training programmes do not only focus on digital technologies and computer manipulation. Actually, digital technologies provide the right pretext to draw attention to essential skills that have to be mastered by archaeologists. Archaeology is made up of digital devices but also geography, statistics, semiology of graphics, topography, history etc. The real debate is the constant re-definition of the scope of intervention of archaeologists. Archaeology is a way of knowing history by studying the material remains and not a full science (Ferdière, 2016). By definition, archaeology is connected to other sciences of every kind — human, hard or earth science — which are manifold. In addition, the numerous digital tools and devices produce flourishing possibilities. The challenge of our time is not to disperse or to lose the real substance of field archaeology. Archaeologists have to work with techniques, technology, expertise and scientific knowledge. The development of digital tools such as GIS does not allow approximations and generates the need for ambitious training programmes. Archaeologists do not have to master every device, every tool or software. However, they have to be familiar enough with them to know when, why and how to use them.

In spite of agreements and switches of teachers between universities and INRAP, there is still a lack of correlation between the general knowledge of students and the practical needs of preventive archaeology. The continuing education programme of the French National Institute for Preventive Archaeological Research is in place in order to bridge the gaps we have observed. This is relevant when the training concerns increasingly new digital technologies and no less relevant when gaps concern field recording, one of the fundamentals of archaeology. Obviously, archaeologists don't have to choose between archaeology and digital archaeology. However, the increasing use of digital technologies must not be an excuse for avoiding the basics of archaeology.

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Mieko Matsumoto and Espen Uleberg (eds) 2018. ***CAA2016: Oceans of Data***
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
Oxford: Archaeopress

DOMUS: Cyber-Archaeology and Education

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Abstract
This paper is focused on the development and implementation of the project elaborated by the Laboratory for Roman Provincial Archaeology (University of Sao Paulo) named DOMUS: the first online Brazilian cyber-archaeological application that enables users to navigate in a three-dimensional virtual environment that simulates an ancient house during the Roman Empire.
DOMUS was applied for the very first time at Colégio Unidade Jardim (a high school in Sao Paulo). The activity consisted of asking the students to navigate through the idealised three-dimensional Roman house in order to explore its rooms and objects, and also to perceive inherent subjects belonging to Pompeian domestic art and architecture. In this manner, the stages involved in the implementation of the activity with students will be presented, and how our cyber-archaeological application allowed them to establish the link between archaeological remains and their own daily lives through computer emulation.

Keywords: cyber-archaeology, Roman archaeology, education, virtual reality

Introduction

The Laboratory for Roman Provincial Archaeology (LARP) — located in the University of Sao Paulo's Museum of Archaeology and Ethnology — developed and released its virtual reality application called DOMUS at the end of 2013. DOMUS consists of a Pompeii-inspired Ancient Roman house that allows the user to navigate through its rooms, visualizing specific information such as everyday objects, the religious cults and the locally traded pottery production. The DOMUS application was made entirely by archaeologists, representing the pioneering effort of Brazilian researchers in producing the very first cyber-archaeological project in our country.

Cyber-archaeology is a dialogue between Archaeology and Virtual Reality. Cyber-archaeology is not a passive process: the user does not simply watch a rendered video, listening to the explications about what is seen on the screen (Forte, 1997). In the cyber-archaeological process, the user is part of the knowledge; being responsible for the development of cognition within the three-dimensional reconstruction. In that way, cyber-archaeology is necessarily interactive: it is the result of digital data gathered in the archaeological field, which is then analysed by archaeologists into immersive environments (such as CAVEs or powerwalls) and later made available to the general public using less expensive interactive devices (such as smartphones, tablets and personal computers).

Cyber-archaeology studies have been conducted since the 2000s, when the archaeologist Maurizio Forte (Duke University) established the main premise of this new area. Cyber-archaeology, as the name suggests, is fundamentally a cybernetic cycle — it starts with fieldwork and then continues to data/information collecting, interpretation, evaluation, feedback and, finally, embodiment (Forte, 2010).

Developing DOMUS

The LARP's DOMUS application was developed and aimed for the general public, mainly teachers and students. From the study of archaeological remains from Pompeii and Herculaneum, the researchers established the major points that could be interesting for teachers to work with in classrooms. Once chosen, we began the simultaneous process of writing the supporting texts and modelling the ancient domus (house). Each researcher being specialised in a particular Roman aspect, we were able to account for a wide range of subjects, from architecture to economics.

For the 3D modelling, Autodesk Maya was used for every object while the Unity engine was utilised to develop the interactivity (Figure 1).

We opted to mix our texts with 3D objects in order to give complete information on each room which the user can visit in a first person point of view. The final

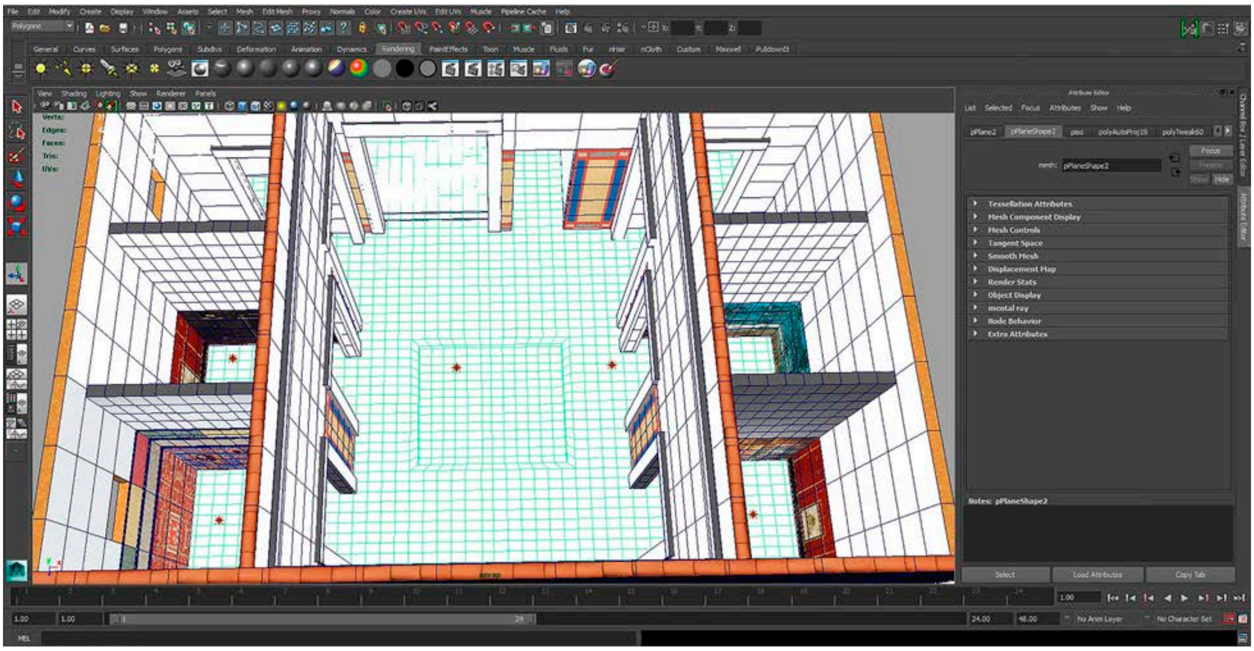

Figure 1. Domus model in Autodesk Maya.

Figure 2. The DOMUS app running in web browser.

application was built for web browsers, being available for Windows and OS X (Figure 2) in our website.[1]

Applying DOMUS: the main goals

Initially, the use of Virtual Reality by the Laboratory for Roman Provincial Archaeology was intended to develop a cooperative project among its researchers, who fulfilled the role of diffusion and scientific dissemination of the laboratory. The subsequent project of conducting an educational activity with this product attended to two key demands: to introduce students to the use of new technologies as an educational resource, and to perform a test to verify the reception by one of the intended audiences (Pantelidis, 1995).

[1] www.larp.mae.usp.br/rv

It is expected that all age groups can benefit and learn more about Rome with the DOMUS application. We proposed an educational project that allows an effective dissemination of research and serves as a guide for the next developments. The main intended goals were:

1. Enable an otherness experience for students, so they can reflect on the historical use of the house;
2. Make use of "L'histoire du quotidian" (the history of everyday life), a much more approachable way to present history to students;
3. Discuss the technological and historical choices that were made during the development of the application;
4. Evaluate the reception of the application.

Amongst the questions raised were: What is a Roman *domus*? What are the parts that comprise it? How did their inhabitants live? What can materiality tell us about them? And what about us? What messages do our houses transmit about the way we live today?

Applying DOMUS: the implementation

The implementation of our proposal occurred in two steps (Fleming, 2016). On the first day, the students worked in groups to walk through the DOMUS in the school's computer laboratory: similar to a digital game, they should find all the explanatory texts scattered around the *domus*. Likewise, the Pompeii image gallery (which is part of the DOMUS) was shown to discuss how the images of the city provided the basis for the 3D application. On the second day, the students handled and compared Roman replicas of objects with contemporary ones that have similar functions (such as oil lamps and current flashlights or Roman and Brazilian coins).

The educational activities with the *domus* during the first day were divided into three stages (recalling the gamification proposed by Kaap, 2012):

1. *Educationalist orientation before activity*. In this initial stage, the educators introduced themselves, gave information about the Museum of Archaeology and Ethnology and the LARP, and explained the activity to the students. Before the DOMUS application, the students were asked what they knew in relation to archaeology in general, and to Rome and Pompeii past history. Many students mentioned the recent film about Pompeii (Bolt *et al.*, 2014), and therefore contributed some information. In general, they understood archaeology as the study of old things (dinosaurs were always mentioned). Rome, for them, is well remembered as a very old city. After carrying out this initial conversation, a challenge was put to the students: they should find all informational texts around the *domus*. As part of the task, the titles of the texts have to be written down by the students. The estimated time for this first part of the activity was approximately 10 minutes (Figure 3).

Figure 3. Educationalist orientation before activity. Educators: Ana Tauhyl and Alex Martire.

2. *Virtual tour*. The students had fifteen to twenty minutes to stroll around the *domus*. The three educators (Tatiana Bina, Ana Paula Tauhyl and Alex Martire) and the teacher responsible for the class (Alessandro Gregori) were available, walking through the computer laboratory if the students had difficulties in the application handling (Figure 4).

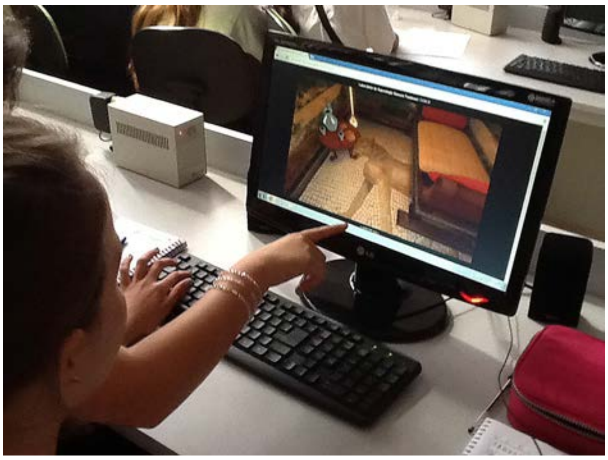

Figure 4. Virtual tour.

3. *Conversation with the educators*. At this point, the students reported to the educators which texts were found. This was also the moment when students expressed their impressions of the application and about activity as a whole. In addition to the *domus*, the image gallery that accompanies the house was shown and educators commented on the relation between the

photographs of the archaeological remains of Pompeii and the three-dimensional model of the application (these photographs also assisted the archaeologists' discussion). Lastly, educators and the responsible teacher warned students that there would be a questionnaire to be answered in the future (Figure 5).

Figure 5. Teacher Alessandro Gregori guiding students.

The school provided excellent structure for activity. Nevertheless, some computers were not able to run the application. Even the online version was quite slow, taking too long to load. The first of the participating classes was divided into pairs initially. However, as the computers showed signs that would not work, the children were being rearranged to the available machines. It took some time. When the other groups arrived, the educators distributed the students in trios for available computers.

The students walked through the house and took notes on the titles of the texts. Most students did not see many similarities between the Roman house and their own house when asked about it. Some asked if the house was real, and the educators explained that it was a model of an ideal house. In general, students realised that it was a house occupied by rich people, and so they said that the life of the Romans was very good. Some photos of Pompeii were shown as the educators talked about the archaeologist's work, restating what the students had said.

The second stage, the handling of objects, followed this script:

1. *Discussion of archaeology*. The students were asked about what they think archaeology is. This conversation was designed to prepare students for the handling of objects.

When the educators arrived, the students in the first class were sitting in a circle outside the classroom. The script was respected, but only the oil lamp and flashlight were fully explored. The coins were just mentioned, due to lack of time. Some students remembered the Roman *domus*, mentioning some objects and features of three–dimensional house. Regarding archaeology, few ventured to comment. The situation with the second class was like the first one.

The last class was received by the educators in the classroom, without changing the spatial configuration of the room (Figure 6). At the beginning they were silent, but parallel conversations increased during the activity. The dynamic continued as planned.

Figure 6. Handling objects. Educators: Tatiana Bina (holding the artifact), Ana Tauhyl and Alessandro Gregori.

2. *Handling objects* (Roman coin, Brazilian coin, ancient oil lamp replica, flashlight). Sitting in a circle, the students were able to manipulate these objects, carefully observing them with regard to form, raw materials, function, value, etc. The time allotted for this part of the activity was approximately 20 minutes.

The students in all three classes commented that it was strange to be passing around a Brazilian coin and a modern flashlight in a class on Roman archaeology. However, when the educators explained the reason for the presence of these objects, the students seemed to understand the intended relationship. The *domus* objects and structures were discussed by the three groups. The fountain of the atrium was frequently mentioned, as were various rooms of the house. As for the objects, very few students recognised the oil lamp (only one student in the last class said it was an object made for lighting, based on a film he had seen).

3. *Discussion between educators and students about the objects*; with the ultimate goal of drawing conclusions from the objects about the human groups that produced them. Some 20 minutes were reserved for this dynamic.

At the end of the three classes, the educators sought to explain to the students that what they had experienced was a little bit of how archaeologists work, by asking questions and testing hypotheses using objects.

4. *Finalisation*; with a recap of all that had been done in the previous phases.

Conclusions

The application of DOMUS in a school made it clear that its technical performance is dependent on the capabilities of the computers on which it is being utilised. Almost half of the school machines had dedicated graphic video cards, but, being quite outdated, they were unable to run the DOMUS in its acceptable frame rate of thirteen frames per second. This negatively impacted the student experience, breaking the sense of immersion and causing some students to lose focus.

This issue is related to the school's computers, not to the DOMUS itself. However, for the next three-dimensional laboratory projects the details of the objects should not be modelled but textured, in order to reduce the number of polygons and consequently improve the application performance.

In educational terms, we can say that even if the technology is not essential, it effectively attracted the attention of students and seems to have had an even greater impact among those who were familiar with video games, presenting itself as an innovative and valuable resource for learning history. Virtual Reality has proven to be a resource trend, especially in the Museums and Archaeological work, to offer something that is otherwise difficult to implement: the feeling of being in a 'past reality'. It is important to emphasise that teachers, educators and everyone involved with Virtual Reality should be clear about its limitations. In particular, this means pointing out that, like all reconstitution, the underlying data are drawn from hypotheses.

Finally, we would like to point out that the use of Virtual Reality to teach History and archaeology does not mean replacing the teacher figure in the classroom: it should be applied as a way of expanding the possibilities and resources of cultural heritage learning (Wickens, 1992; Clark, 1994; Sobota, 2012).

Teachers should be able to construct knowledge with their students, mediating discussions and observing the main points that can be improved from the use of interactive technologies in the classroom. Only in this way will the Virtual Reality provide students a thorough understanding of the subject studied and the various readings that we can infer about the past.

Acknowledgements

The authors would like to thank Professor Maria Isabel D'Agostino Fleming, M.S. Ana Paula Tauhyl, M.S. Alessandro Mortaio Gregori, Willie Linn, LARP MAE-USP, MAE-USP, FAPESP.

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Mieko Matsumoto and Espen Uleberg (eds) 2018. ***CAA2016: Oceans of Data***
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
Oxford: Archaeopress

Digital Data Recording at Circus Maximus: A Recent Experience

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Abstract

Between 2011 and 2015 a stratigraphic excavation was carried out in the area of the Circus Maximus in Rome by the Sovrintendenza Capitolina, in agreement with the Università Sapienza of Rome. The excavation involved 50 archaeology students who were trained in the use of new technologies for the field data recording: this activity focused on the use of photogrammetry. The choice was motivated by the hybrid nature of the archaeological site — an educational excavation but also a public work of an urgent nature: the restoration works were urgent and this forced the speed of the archaeological research. Digital photogrammetry, after comparing costs and benefits, proved to be the best solution for the archaeologist's needs. This paper aims to share our opinion on the reliability of the methodology that was used, the changes it brought to the organisation of the team's work, and the issues related with the archiving and sharing of data.

Keywords: teaching methods, digital archaeology, photogrammetry, Rome, Circus Maximus

Introduction

The *Circus Maximus* was the largest chariot racing stadium and mass entertainment venue of the ancient world. It has an unbroken continuity of life (and several different lives), from the Roman Kingdom period to the present day. Its fortune and misfortune are due to its location. Effectively, it was located next to the most important crossroads of proto-historic age in central Italy: here the north–south road from *Etruria* to *Campania* crossed the navigable Tiber through the ford of Tiber Island. That is probably the main reason why Rome was settled there, and it's still there (Figure 1).

The Circus lies tight between Aventine hill on the south and Palatine hill to the north. According to many Latin authors, this area was called *Vallis Murcia* (Murcia Valley). During the Roman Kingdom, or even earlier, *Vallis Murcia* hosted worship and special holidays, such as the games in honour of the god *Conso*, during which chariot races were held. The first verified chariot race is attributed to *Tarquinius Priscus*, the first Etruscan king of Rome (Ciancio Rossetto, 2001).

From a hydrological point of view, this valley gathered waters from the Labicana Valley and from the *velabrum minus*. Today they are better known as Colosseum valley and Caracalla baths valley (Figure 2). For these reasons, the bottom of the valley was filled by alluvial sediments. These conditions have several effects on the shape of the building, and on the huge numbers of restoration campaigns that it has needed.

During the late Roman Republic, the Circus was probably a simple structure, and less complicated than the construction of the Imperial period: at this stage Caesar and August created a new architectural shape for the circus, consisting of an enclosed space with self-supporting masonry structures, no longer bound by the surrounding slopes, as it was in Greek circuses (Ciancio Rossetto, 2002). Dionysius of Halicarnassus, who lived in Rome in that period, talked about the dimensions of the new building: the length was six hundred and twenty one metres (621 m) and the width was one hundred and eighteen metres (118 m), and the capacity reached 150,000 people (Bigot, 1908).

The building was destroyed by a series of fires under Nero and Domitian. In particular, the great fire of Nero began precisely in the curved side of the Circus Maximus. In the year 80 AD, a triple arch was set in the centre of the hemicycle to commemorate the Emperors Vespasian and Titus' victories during the Jewish War (Golvin *et al*., 2001). It was later rebuilt by Trajan in one hundred and four AD, and later enlarged by Caracalla (Figure 3).

The ancient Marble Map of Rome and other documents throw light over the shape of the Circus during the late Roman Empire: we could have seen the spina — the middle axis — decorated with two Egyptian obelisks, the marble carceres, the gilded bronze metae (the cone-shaped markers at the ends of the spina). The pulvinar — the Emperor's box — was installed on the palatine

Figure 1. The Circus Maximus, bird's-eye view.

side, and it was reserved for the gods that presided over the games (Brandizzi Vittucci, 1991).

In 549 AD, Totila, the King of the Ostrogoths, held the last known chariot race. After the 6th century, the Circus fell into disuse and decay, and was quarried for building materials. In the Middle Ages the lower levels, ever prone to flooding, were gradually buried under waterlogged alluvial sediments. In that period, the Circus Maximus was used as an agricultural area. Just to give an example, the original chariot track is now 8m beneath the modern surface. Around the mid-point of the 1100s AD, the area was the property of the Frangipane family, one of the most important noble families in that period. They transformed it to a fortress with a tower, and it was called 'Turris de Arcu' (meaning the tower of the arch).

During the 14th century, a mill was added to the tower and the Mariana acqueducts — an open air canal coming from the Caracalla baths valley, activated it. The Diakonia of St. Lucia *in septem soliis*, an early medieval building to support pilgrims, was set on the Palatine side of the hemicycle, but was demolished during the 15th century.

The Circus Maximus suffered through the industrial era: the area was developed by warehouses, factories and one huge gas depot. After 1870, Rome became the capital city of the Reign of Italy; a few years later an archaeological park was planned. Between 1909 and

Figure 2. The Circus Maximus nowadays.

Figure 3. The Circus Maximus 3D model, section slice.

Figure 4. The excavation involved 50 archaeology students from the ancient topography curriculum of the Università Sapienza of Rome.

1934 the area of the Circus Maximus was freed from industrial buildings, and the Tower was isolated and put under restoration.

During the fascist period, The Circus Maximus area hosted several exhibitions: for example the Mineral expo was held in Rome in 1938. In the city of Rome, archaeological propaganda projects involving the clearing, isolation and restoration of key monuments all through the town received strong support from the regime (Muñoz, 1934). Reviving the glories of the Roman Empire at that time was a common theme. In order to reach the Roman layer, the archaeological excavation moved on by often deliberately destroying surrounding Medieval buildings.

Nowadays, the Circus freed of other ancient buildings, the area is a large park in the centre of the modern city. It is often used for concerts and social meetings. The most important visible remains of the Circus are those of the eastern half of the curved side as it appeared during the reign of Trajan (Ciancio Rossetto, 1986).

On the Palatine side, the visible remains belong to the *media cavea* and *summa cavea*; on the Aventine side *ima* and *media cavea* are still standing. The whole area is currently undergoing restoration works in preparation for the public opening; restoration work and archaeological excavation were part of a large-scale project for the environmental requalification and promotion of the archaeological remains.

In the field

Between 2011 and 2015 a stratigraphic excavation was carried out by the Sovrintendenza Capitolina ai Beni Culturali in agreement with the Università Sapienza of Rome, chair of Ancient Roman City planning. The excavation involved 50 archaeology students from the ancient topography curriculum (Figure 4). While working on the educational dig, the young archaeologists were trained in the use of new technologies for field data recording: above all this activity focused on the use of photogrammetry and image based modelling techniques (Campana *et al.*, 2012; Fryer *et al.*, 2007; Russo and Remondino, 2012).

Purpose

The main purposes of this research were, on one hand, increasing knowledge about the ancient building, recording data about walls' condition before restoration works, and recording archaeological excavations along the future touristic itinerary. On the other hand, one of the goals was to train students about stratigraphic methods, traditional and new 3D survey methods and data recording techniques, to teach them how to store and to manage archaeological items during post–excavation phases, and to get them used to a real urban archaeological excavation.

We had three different environmental challenges: the first was living with the restoration works. Moreover, these urgent works forced the speed of the

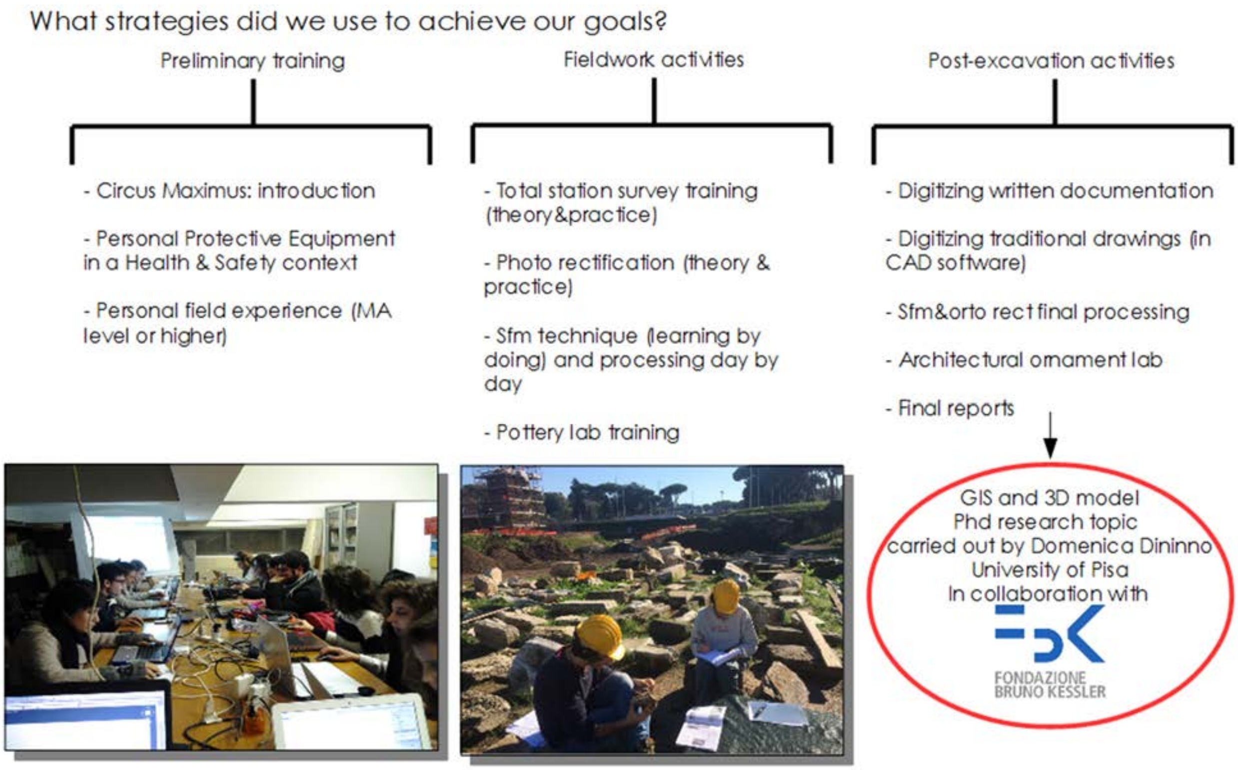

Figure 5. Strategies and workflow.

archaeological activities and that is the reason why several different trenches were open in the same area during different campaigns. We had to adapt ourselves to the restorations' needs.

The second challenge was the water. The hydrogeological and geological situation of Murcia Valley had a broad negative effect on the normal workflow: first of all the average activity level was between 12 and 15 m above sea level (a.s.l.), whilst the aquifer level was between 13 and 14 m a.s.l., depending on the season and rainfall levels. Secondly, this influenced our trench planning and the quality of the pictures taken for documentation purposes.

Blending multiple data sources with different levels of accuracy was the last challenge we faced — in fact we had to combine data from historical sources, from the early 20th century excavations, and from the recent excavation. After this stage, it was decided to test photogrammetry in data recording in order to create a complete and impartial documentation for future excavation and research of the area.

Methods

What strategies did we use to achieve these goals? Before the excavation began there was little time: we decided to apply the 'learning by doing' teaching method. During the excavation, the focus was on teaching traditional survey methods like direct drawing, total station survey (Giuliani,1994; Bianchini, 2008; Sgalambro; 2009) and photogrammetric survey methods (Figure 5).

In a post-excavation stage we held a 'digitising lab' converting written documentation, traditional drawings (into CAD software) and processing data recorded on the field (ortho-rectification and photogrammetry). All these data will flow into a GIS and a 3D model of the area.

In order to be clear, our focus was on the 3D survey technique in the archaeological fieldwork, our workflow was based on recording data by a remote controlled DSLR Camera plus using a TS06 Leica Total Station. Images were processed using Agisoft Photoscan, and exported meshes were processed using Meshlab (Cignoni *et al.*, 2008; Remondino, 2014a, 2014b; Dellepiane *et al.*, 2013). Direct drawings and ortho-rectified images were traced into CAD software in order to get a metrical drawing.

Currently, Domenica Dininno — a PhD student of the University of Pisa, is studying the monument in collaboration with the Bruno Kessler Foundation of Trento, Italy.

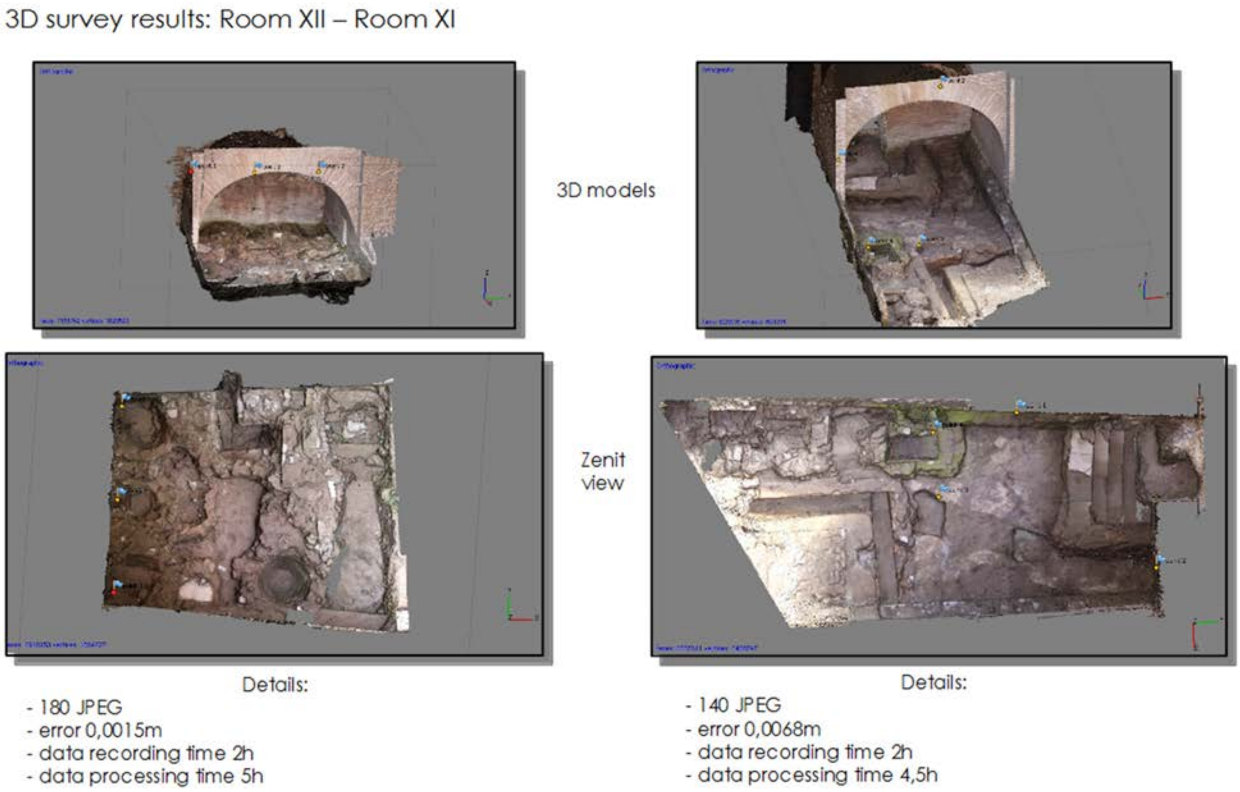

Figure 6. 3D survey results: Room XII–Room XI.

The research project, named ‘The Circus Maximus in the urban arrangement of the *Regio* XI: diachronic reconstruction and topographical development through the application of new technologies’, is focused on the Circus with a new methodological approach for the site, i.e. photogrammetry (Nocerino *et al.*, 2014), 3D modelling and a relational database. The investigation, through a total review of historical data and new surveys, aims to tackle the study of how the construction of the building has changed the shape of the *Regio* XI. The final digital product will contain historical data of the ruins in one accessible portal/informatics system.

Results

The excavation gathered data from 24 trenches, with 20 complete rooms recorded. A new topographical base network was made. We reached over 400 Stratigraphic Units recorded using different survey methods.

The 3D Survey results are divided into two kinds of context: the first was focused on trench excavation; the second was focused on architectural survey.

In Room XII and Room XI of the palatine side of the hemicycle, we decided to record just the final stage of the excavation by using photogrammetry technique (Figure 6). All the layers above were drawn by total station or by using direct drawing. This is because the upper stratigraphic units were deeply disturbed by early 20th century excavations. These two rooms were quite similar, so we had to process less than 200 pictures and extract from the model just a zenit orthophoto and a couple of section slices.

Digging in the area of the Arch of Titus was quite different. This large area (80 m^2) was very interesting for its well-preserved continuity of activity: during the late antiquity period the Arch was exploited as a huge quarry. The excavation was carried out by using pumps in order to reduce the aquifer level. This element forced us to quickly record the layers and is therefore the reason why we decided to record every single layer by photogrammetry as we needed to precisely map the Roman and Medieval buildings and dumping layers (Francovich and Manacorda, 2009).

Hydrological problems and safety fencing (and its shadows) didn’t help in recording clear pictures: we had precise metrical shapes of the layers but incomplete or imperfect orthophotos. The whole recording process consisted of 1160 pictures taken of 20 layers during two months of excavation. We extracted at least 16 different section slices from two trenches. For safety reasons, we could not have both trenches active at the same time;

but thanks to the photogrammetry we could visualize at the same time, for example, the same floor layers found in the two trenches.

The second sort of example is focused on architectural survey, so we consider these 'static' items. This might appear easy — but that is a half-truth: the internal ambulatory has no roof, so in this case we had just two hours in the morning of sufficient light and no shadows. In this case we needed a uniform light in order to record the real colours of the bricks from several phases and restoration works. This survey was probably our best performance in terms of timing, metrical accuracy and picture quality. The only negative aspect was the merging process that required a high level of computational capacity.

The final example is a hybrid one: an architectural survey that was merged with an unexpected excavation survey. In September 2014, we had to draw the eastern wall of the tower; that facade was very interesting because there are several ducts which fed the medieval mill. In December 2014 we opened the first trench beside the Arch of Titus, which is next to the eastern facade of the tower. In this case, we re-used our old photos and succeeded in meshing-up the documentation. In a few steps we had a complete survey of that area.

To conclude — what went right with this digital data recording? Timing was crucial: the environmental challenges forced us to modify the normal workflow; the strategies we chose helped us to record a large and complete data set. Secondly, these techniques are cheaper than many others and therefore allowed us to save time and money.

Furthermore, in order to ease the data blending process from different sources, photogrammetry is currently the best solution: pictures provide a permanent recording of the existing structures and soil conditions. Photogrammetry produces a file that could be used and integrated year by year. Moreover, pictures and 3D models can be used to convey information to the general public.

Conclusion

At the end of the workflow we collected some practical questions and answers:

Is the 'Learning by doing' teaching method the best solution for photogrammetry? Perhaps it is not, but at that time it was the best solution available. Before the excavation we had no time for a whole Structure From Motion (SFM) theory class but we were obliged to do so. Some students were not able to manage a DSLR camera or they needed more theoretical knowledge about this method. Our present survey projects include a preliminary theory class and a photography class, which could help in decreasing the number of pictures and mistakes during data recording.

A single layer or room file can be easy to manage; but what about an entire project? Sometimes students laptops and desktops were not completely sufficient, therefore a huge excavation project has to consider funds for workstations and online storage space.

Is recording every single Stratigraphic Unit by photogrammetry useful? It depends on the excavation; for most of our trenches using different survey methods was the best option. Recording every single layer by photogrammetry extends processing time and postpones the final interpretative process.

Was photogrammetry always the best solution? Of course not; sometimes environmental factors (like shadows and mirroring surfaces) make photogrammetry an imperfect solution.

The Circus Maximus digital data recording project showed many methodological and logistical issues. A certain dose of adaptation was necessary, so we think the answer to these questions and requirements that the photogrammetric survey method offers the advantage of flexibility.

That said, the direct survey of the monument is crucial: metric survey is an instrument — not the final point — and it provides a dialogue between us and the monument which is why it has to be carried out by the same people who excavate the monument. It is necessary to maintain a direct contact with the structure (Giuliani, 1976; Giuliani, 1994). Similarly, 3D models are not the final goal or purpose, but just a tool useful to understand the monument.

In archaeology, as in many other disciplines, the adoption of new research methods usually raises two main reactions: refusal or enthusiasm. After a period of testing, a certain awareness of this new method or item is reached (Giuliani, 1976). This huge fieldwork project provided us with numerous feedback points on the photogrammetric survey and structure from motion technique.

In particular, we were not just users; we were also in a teaching position. Based on our experience we think that it is necessary to reach a thorough understanding or consciousness of this new method in order to teach it in the right way to students that will be future archaeologists. Comprehension is the essence of the archaeological process, and in our current opinion, the best way to reach this goal is using different subject dependent recording tools.

Not only archaeology students and teachers, but also the institutions that commission jobs in this field should be aware of the potentiality and reliability of those methods and techniques. Commissioners (especially from the public) should also have the capacity to store, manage and share this kind of data.

A multidisciplinary approach should be assimilated from the beginning of an archaeologist's learning path: it's crucial that our universities offer, together with classical teachings, adequate complementary subjects, such as CAD classes, photogrammetry classes, GIS classes. This is what we are trying to achieve during our current and future surveys and mapping projects.

Acknowledgements

Special thanks to Marialetizia Buonfiglio and to the Sovraintendenza Capitolina ai Beni Culturali di Roma Capitale.

We are also grateful to Luisa Migliorati (Sapienza University of Rome) for her support and her comments.

We have to express our appreciation to our colleagues for their support during the fieldwork.

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Mieko Matsumoto and Espen Uleberg (eds) 2018. ***CAA2016: Oceans of Data***
Proceedings of the 44th Conference on Computer Applications and Quantitative Methods in Archaeology.
Oxford: Archaeopress

Teaching GIS in Archaeology: What Students Focus On

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Abstract
The future of GIS applications in Archaeology is developing among current students. For that reason, the postgraduate classroom can be an appropriate laboratory in order to approach trends.
We explore here recent tendencies in GIS students and analyse the impact of the current teaching resources on the student's topic elections. Both authors of this paper together taught 'GIS and territorial analysis' as a subject at Master Degree level. The students' course work from five consecutive academic years (a total of 78 coursework projects from 2010/11 to 2014/15) have been analysed from different points of view in order to understand students' preferences when using GIS. All students followed the Master in Archaeology and Heritage at the University Autónoma of Madrid (Spain).
The main aim of our paper is to encourage the scientific and educational community to develop similar experiences, in order to get comparative data from other educational contexts about current trends in GIS beginners.

Keywords: GIS, postgraduate teaching, GIS in archaeology trends

Introduction. The present and future of GIS in archaeology: a continuous interest

Assessing the State of the Art and trends in archaeological GIS applications have been common place in literature since the middle of the nineties, and from multiple points of view (Djindjian, 1998; Arroyo-Bishop, 1998; Barceló and Pallarés, 1998; Johnson, 1998; Kvamme, 1998; Lock, 1998; Madsen, 1998; Moscati, 1998; Stančič, 1998; Baena Preysler, 2003; Katsianis and Tsipidis, 2005; Zamora Merchán and Baena Preysler, 2010; Hu, 2012; Pastor *et al.*, 2013; Zamora Merchán, 2016; amongst others).

Usually, papers about GIS tendencies have been focused on the community of researchers and professionals. However, the future of GIS applications in Archaeology is developing among current students. For that reason, the postgraduate classroom can be an appropriate laboratory in order to approach tendencies. Both authors of this paper together taught 'GIS and territorial analysis' at Master Degree level. What we present here is an assessment of interest and tendencies in GIS applications among current postgraduate students (from 2010 to 2015) at the University Autónoma of Madrid. This includes what they want to achieve, which are their interest areas and periods, and how they use GIS to resolve archaeological problems. With the freedom to choose, are they facing the most complicated tasks?

Although this paper examines just a single teaching experience (which is deeply dependent from our particular educational context), we would like to share it with the GIS in Archaeology community. If similar experiences are shared, then comparative data from other educational contexts will be available. Those data could make us all aware of about current trends with GIS beginners, and help to correct (if necessary) the future situation of GIS uses in Archaeology.

The future comes from today. Teaching/learning GIS in archaeology at the University: the case of UAM

GIS applications in Archaeology have a long tradition in the Department of Prehistory and Archaeology at the University Autónoma of Madrid (UAM). Since the beginning of the nineties, we started to develop several Research Projects, Postgraduate Thesis, and PhD projects related to GIS applications in Archaeology (Baena Preysler *et al.*, 1997). This achievement was mainly thanks to the facilities of the UAM Cartography Service (SCUAM) located in the Department of Geography, at that time our only (and great) chance for GIS in archaeological development.

Since 1997, this research interest was also extended into the teaching field. Several PhD courses were taught during the following academic years (thanks again to the computer facilities of the SCUAM).

Later on, after the launch of the European Higher Education Area (EHEA) according to the Bologna Process, GIS in archaeology teaching was integrated as a subject for our Master degree in *Archaeology and Heritage*, and it has been (and it still is) one of the most requested subjects among students. The Master is conducted by the Department of Prehistory and Archaeology, and it includes subjects in Archaeology of all periods, as well as an important amount of transversal topics covering the areas of field archaeology, museology, heritage conservation and legislation, amongst others. The degree joins students from a wide array of Humanities' backgrounds (mainly History and Antiquity related degrees).

'GIS and territorial analysis' is an elective subject, where theory and practice of GIS usage in archaeology are combined. It is presented as an introductory course, where learning outcomes include knowledge and scientific–technical skills. Class attendance is mandatory, and two teachers are present in the classroom. As the primary means of evaluation, the student has to elaborate an individual (and supervised by us) coursework project showing a personal GIS application to a particular archaeological context (see below). Usually, the GIS program we teach is ArcGIS by ESRI because it seems to us the most complete GIS software available at our university. However, for their personal assignments, students are free to use whatever GIS software they want to use.

3. What students focus on? The characteristics of their free-choice coursework (2010–2015)

The students' coursework must contain the following points: an archaeo-historical context; problem(s) to resolve; reasons for using a GIS; available data (cartographic and archaeological) to develop the project; how GIS has been implemented; advantages and disadvantages of the project; cost estimate (in working hours); results (done or expected) and a bibliography. In addition, in order to guide students through the assignment, an evaluation rubric is given to them (where it is deeply specified the type of possible contents and their corresponding qualifications).

Under the supervision of both teachers, in order to avoid disproportionate works, students are free to choose what to do with the GIS, where, when and how applying it, the scale of analysis, the problem to solve, and the GIS tools and steps done to solve the selected problem. Since this work as a whole can be a difficult task for beginners, hypothetical problems are also welcome when properly reasoned (although this option has been scarcely used).

The students' coursework from five consecutive academic years has been analysed, taking into account the following aspects:

- Main work lines
- Spatial scale
- Location of study areas
- Chronological array of analyses
- Main GIS application.

The total amount of coursework projects considered here is 78. Every academic year had a different amount of students enrolled. So, the amount of students who passed the subject (and handed in their coursework) by academic year was as follows: 2010–2011: 19 students, 2011–2012: 19 students with coursework as well, 2012–2013: 12, in 2013–2014: 15 and finally in 2014–2015 we had 13 students with coursework.

Main work lines

It is well known that GIS in Archaeology have a wide array of fields of application. However, the main areas of development still can be defined according to the traditional division between Cultural Resource Management (CRM) and fundamental research.

Our Master degree has a double orientation towards both fields. In one hand it has a strong component about fundamental research, and in the other hand it deals deeply with cultural heritage matters as well. Therefore, the Master attracts students with both professional interests. This statement provides a background for checking how relevant this dichotomy is among students enrolled in the subject called 'GIS and territorial analysis'.

Our particular impression in recent years had been to notice a progressive decrease of the students' interested in fundamental research oriented works, in benefit of those ones related to heritage management (including works focusing on archaeological tourism). This impression was purely a subjective effect, since data indicates the opposite. Despite of fluctuations between years (see Figure 1), fundamental research oriented coursework projects have been the most frequent works (more than double compared to the rest).

It is true that a great number of students try to include as many GIS procedures seen in class as possible into their work. This option is only available if they choose a research oriented line (in order to include spatial analysis tools, like viewshed and shortest path, as well as geoprocessing). As teachers, our tendency is to try to calm students' efforts at covering all options, since we want them to construct strong projects rather than pretentious, and usually students cannot adequately

Main work lines	2010-2011	2011-2012	2012-2013	2013-2014	2014-2015	TOTAL
Research (%)	50	67	92	67	62	67,6
CRM (%)	50	33	8	33	38	32,4

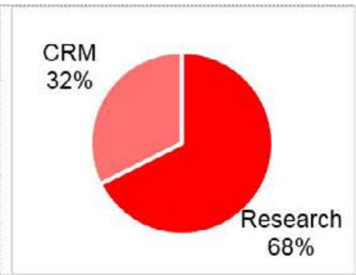

Figure 1. Main work lines (Research and Cultural Resource Management CRM) detected on students' coursework projects during five academic years.

evaluate their initial work proposal (often too ambitious for a semester). Therefore, a student who at first did not display any clear idea for their coursework, was redirected by us to initially achieve basic tasks (GIS data management mainly). Even so, the interests of our students turn to the research field rather than CRM.

Chronological period

The Master's program is open to archaeology of all periods of human History. Subjects with historical contents cover from Prehistory to the Middle Ages, but also a number of important methodological and technical subjects can deal with any historical period. This aspect engages students with different chronological interests, which has been evidenced in the coursework topics chosen by GIS students (Figure 2).

In the course of doing this study, some difficulties arose when assigning works to a particular period. That has been the case for:

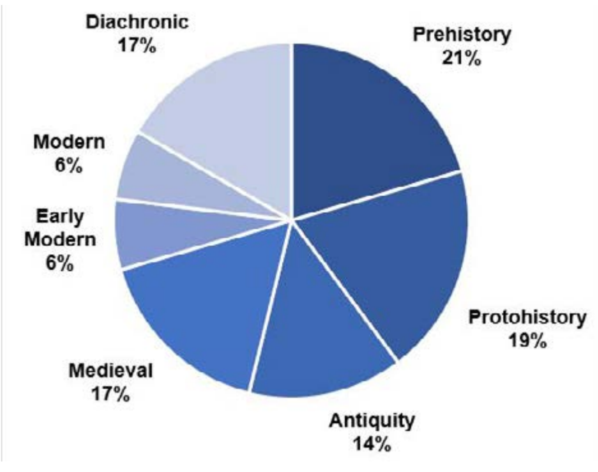

Figure 2. Distribution of students' coursework projects by historical period. The limit of the Proto-history section could be varied, especially in favour of Antiquity section (see text). Also, works considered as Diachronic are not counted in other sections.

- Coursework projects with no precise chronological limits. The fuzzy line between conventional historical periods can have caused fluctuations in the number of counted projects. This could be the case between the end of Prehistory and the beginning of Proto-history, for example, and especially between Proto-history and Antiquity.
- Diachronic works. For this type of approach a single group has been created, noticeable as it includes as much as 17% of the projects.

The assignments dealing with Prehistory reach 21% of the total amount. A similar quantity corresponds to works focusing on Proto-history. Together these add up to 40% of students' interests. Third place is held by the Medieval period, with 17% of coursework projects.

Noticeable is the apparently minor interest in Antiquity shown in Figure 2, since this period has a strong and attractive archaeological matter, with a huge material culture represented in the Iberian Peninsula. We assess this issue according to the following aspects:

- The aforementioned warp on the limits between Proto-history and Antiquity. Some students' works belonging to Proto-history could have been included in Antiquity as well (in case of those dealing with the Late Iberian or Ibero-Roman period), since in our assessment we have given preference to the local culture of the work's study area. Given that in most cases the local place has been the Iberian Peninsula, the beginning of Antiquity appears postponed till the effective conquest of the Iberian territory by Romans (that is not the case, for example, of research dealing with the material culture of ancient Greece from the 7th to 4th centuries BC, which, logically, have been listed as Antiquity).
- There is (at first glance) little use of GIS in classical archaeology compared to other periods.
- Some coursework projects dealing not just with Antiquity, but also with other periods have been considered diachronic.

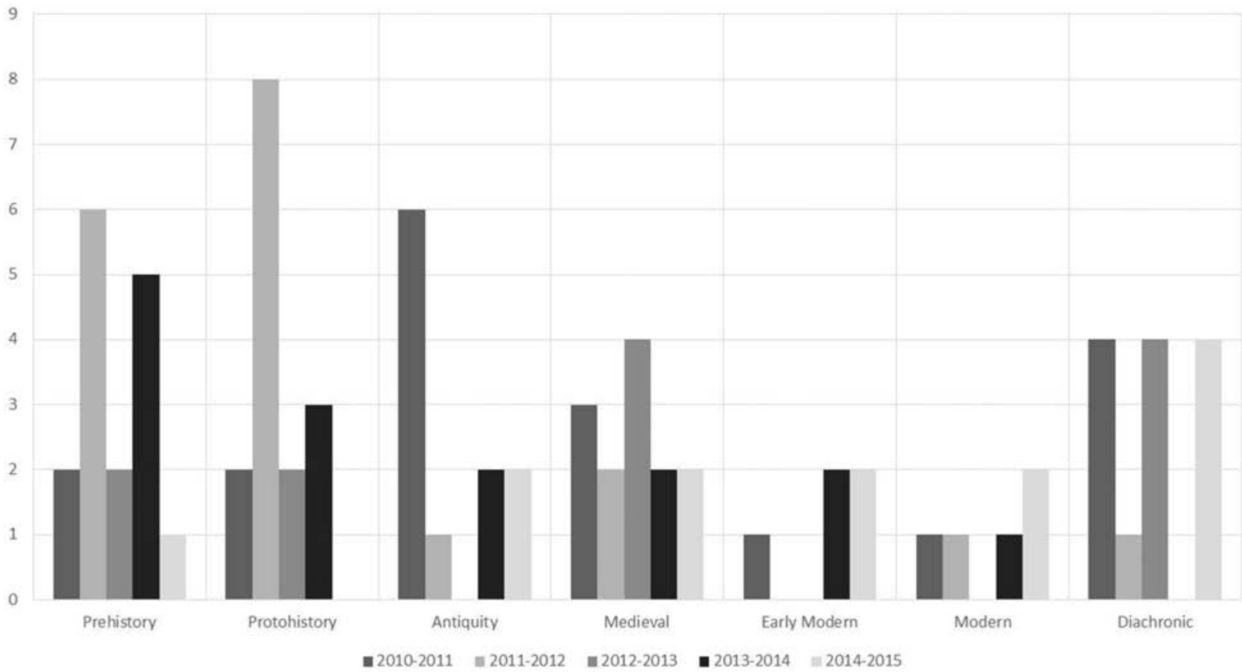

Figure 3. Number of coursework projects by period of interest and academic year.

Works focusing on the Middle Ages (6th–15th centuries) are quite representative, with 17% of the total. In this group there has been a special interest for inter-visibility studies between watchtowers, one of the most usual GIS applications for this archaeological context.

Finally, the Early Modern Period (16th–18th centuries) and the following centuries represent a small percentage. Often, works focused on the Early Modern Period have dealt with the georeferencing of historical cartography from the 17th and 18th centuries. Those dealing with the 20th century, usually focus on the archaeology of the Spanish Civil War (1936–1939).

Figure 3 shows the coursework projects organised by the historical period of interest and academic year. We can see that Prehistory and the Middle Ages have at least one specific project every course. On the other side, the Early Modern is the most fluctuant period, which fits quite well with general tendencies of Spanish archaeology. Be aware that course-works dealing with several historical periods have been included just in the group 'Diachronic'.

Scale of analysis

In considering the scale of analyses, we have distributed students' work into two groups:

- The works approaching a single archaeological site (including here the analyses of the site's closest territory as well as intra-site).

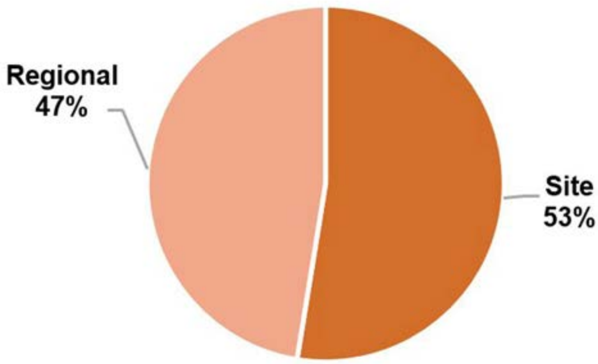

Figure 4. Scale of analyses showed in students' assignments.

- The works dealing with more than one site, that is, regional analyses.

Results are shown in Figure 4. There is a slight dominance of site analyses over the regional ones, which makes sense with an equilibrated approach.

Main GIS final task

Which type of GIS commands are chosen by students for doing their assignments is directly related to the contents of our practical lessons. Exceptions apart, students have chosen GIS procedures from the array of possibilities learned in class. During a 'semester' of just three and a half months, we introduced students to the following practical tasks:

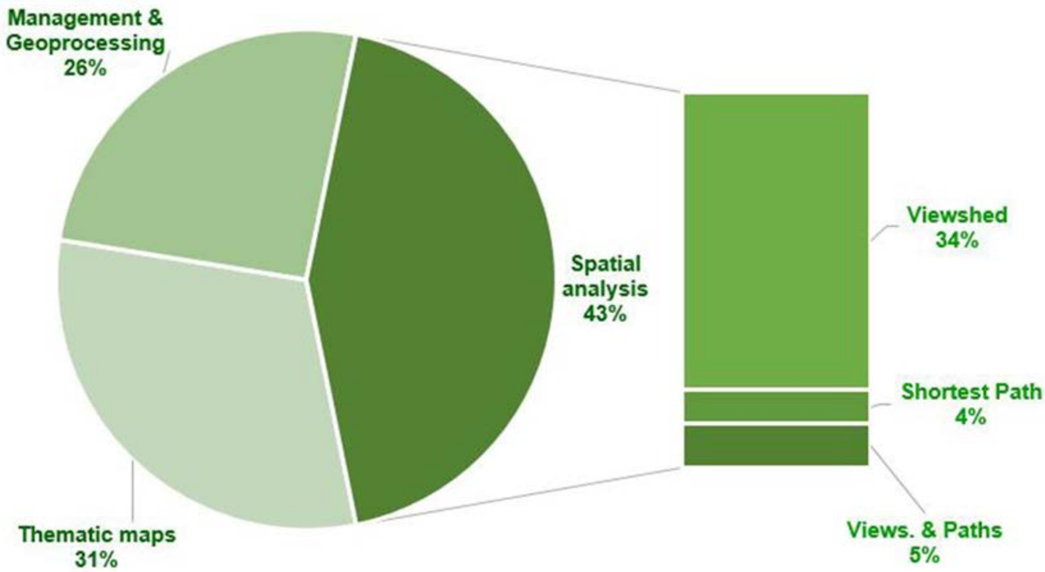

Figure 5. Main GIS procedure included in the students' coursework projects.

- First approach to different GIS data files.
- Attribute tables and its initial management (add/delete fields, type of field, selection).
- Elaboration of a simple thematic map.
- Geographic file creation (shapefiles mainly).
- Geoprocessing tools (buffer, clip, merge).
- Georeferencing.
- Creation of Digital Terrain Models.
- Hyperlinks and other similar tasks.
- Viewshed analyses.
- Shortest Path calculation.

Figure 5 shows the main GIS tools used by students in their free-choice assignments. The most complicated procedures usually include some simple tools as well. Since spatial analysis is the most advanced procedure from those learned on the course, we can see that 43% of students opted for integrating such analyses (more or less successfully) into their own projects. We have taught spatial analysis at the end of the semester. Despite this fact, a high amount of these procedures are viewshed analyses, while shortest path has a minimised representation. This point fits well with:

- The more attention we have paid to visibility studies when teaching
- The usual attractiveness of such analyses among landscape researchers (or future researchers)
- Its greater facility to be developed when compared to the shortest path tool.

Although the total mean seems to be quite equilibrated, that has not been the case during every particular academic year (Figure 6). The variability is so high that we cannot offer any explanatory conclusions, although it must be taken into account that students' sharing an academic year choose similar tasks (thematic maps in 2014/2015, Geoprocessing in 2010/2011, and Viewshed in 2013/2014).

Conclusions

For us, following on from the previous analyses, two questions arise:

Do Students' work match with current tendencies? Having a quick look to professional GIS experiences in archaeology today, we can see that spatial analyses continue as the main development application. However, some new uses such as complex activities developed by coordinated team-work (case of Spatial Data Infrastructures (SDI) and other Internet related projects), hybrid uses of GIS with other kind of technologies, and reaching application areas where GIS is not the main agent (the case of 3D visualization), form today an important research field (Zamora Merchán, 2016). However, they are beyond the scope of our beginner students, since working in a team (on multidisciplinary teams) is mandatory to develop these types of projects.

What happens in the classroom is, firstly, a reflection of what teachers do there. Despite global access to knowledge through the Internet, classroom teaching still has a deep responsibility, especially when orienting beginners. What we teach our students is going to set their foundations and future lines of work, since, in general terms, they will tend to repeat the first adopted methodology. Taking into account that GIS teaching is not a simple subject, the first approach to the topic

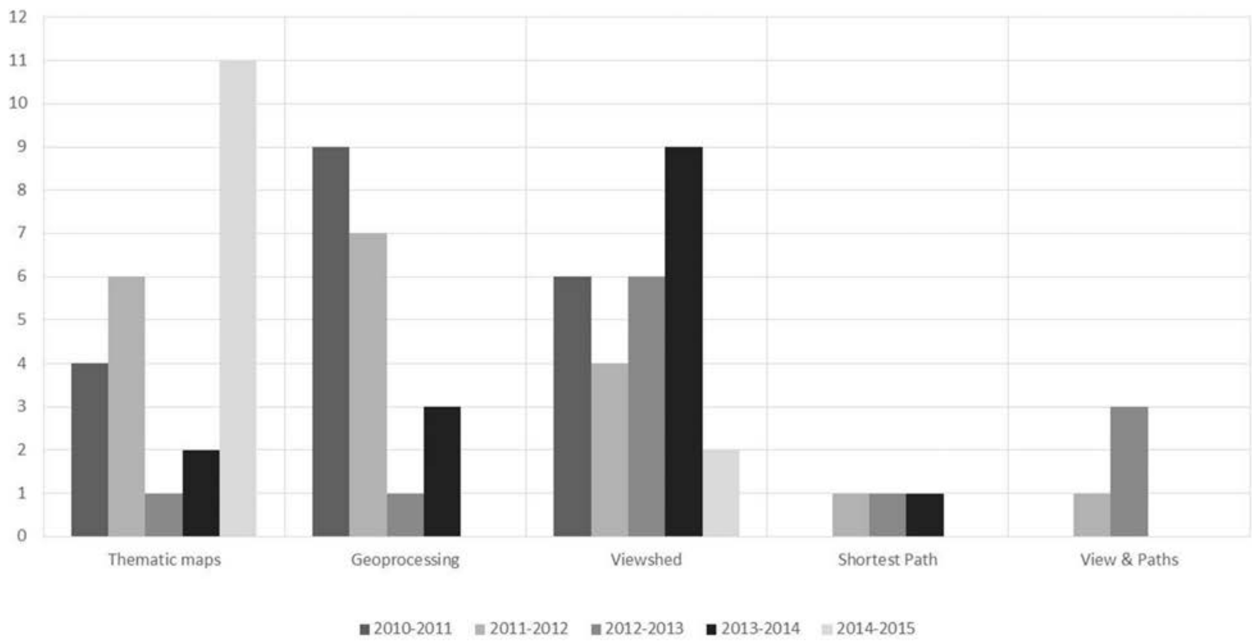

Figure 6. Number of coursework projects by main GIS application and academic year.

should focus on basic concepts in order to establish a good background and to keep students away from superficial practices and empty results.

Are our students facing the most complicated tasks? We think they are. Although current students are digital natives, the management of GIS programs, as well as its application to archaeological contexts, still bring important obstacles to beginners' learning. Overcoming some old problems (e.g. the access to detailed digital cartography) makes the first approach to the topic more attractive. However, understanding key practical concepts (like characteristics of data models, as well as the huge amount of different technical matters related to the use of this large software), make the subject sometimes an overwhelming challenge, since students can see the high potential of GIS and available data but also their own personal limits. What they cannot really see (even if told) is how lucky they are running GIS on very fast computers, with user friendly PC's software, and using unbelievable LIDAR data for DTMs (things that we could not even dream when we were GIS beginners).

We hope this paper could encourage scientific and educational community to share similar experiences, in order to make available to the international community some comparative data from other educational contexts about current trends on GIS beginners.

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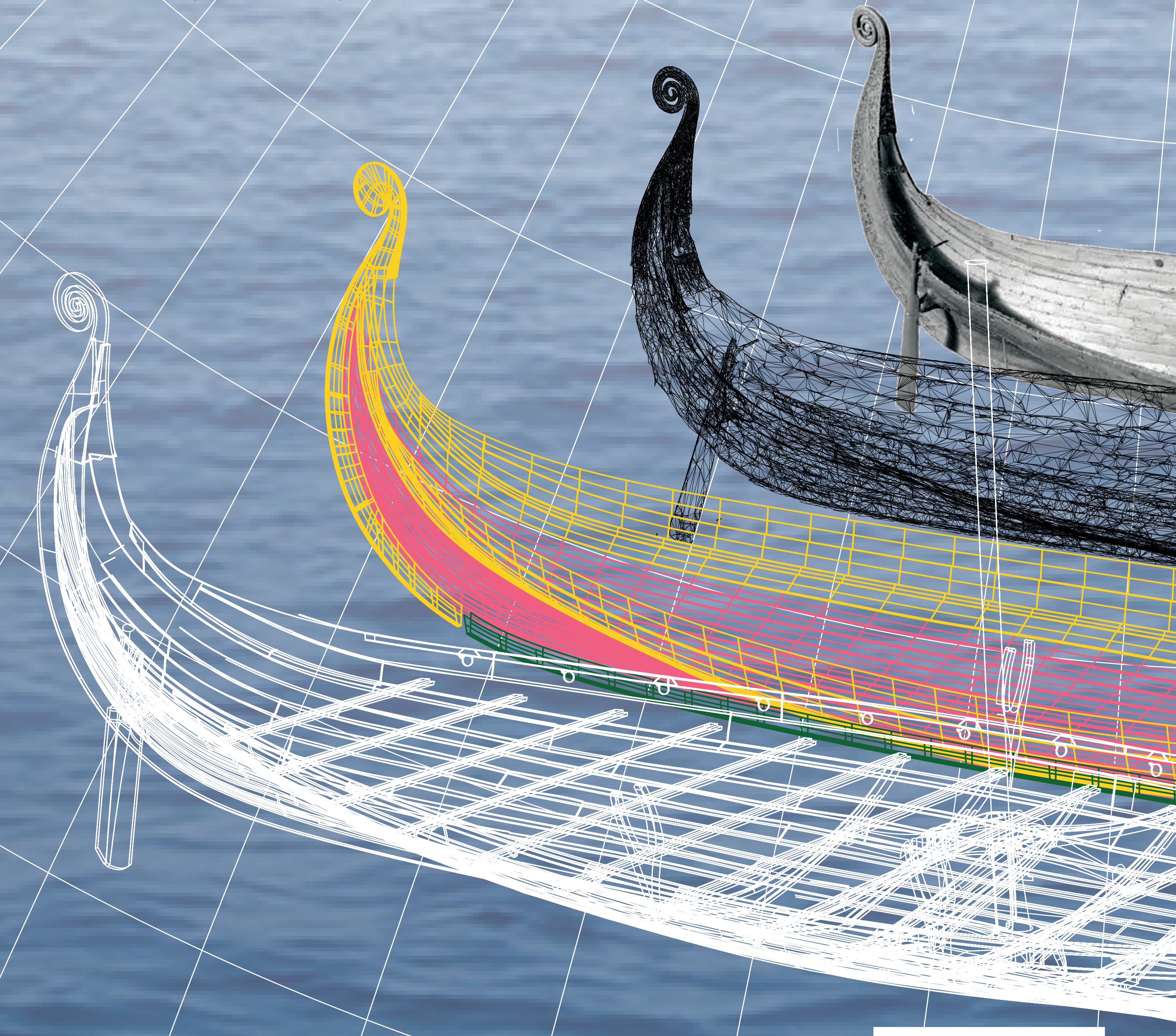

ISBN 978-1-78491-730-2

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