CAA 2017

DIGITAL ARCHAEOLOGIES, MATERIAL WORLDS (PAST AND PRESENT)

PROCEEDINGS OF THE 45TH ANNUAL CONFERENCE ON COMPUTER APPLICATIONS AND QUANTITATIVE METHODS IN ARCHAEOLOGY

GEORGIA STATE UNIVERSITY, ATLANTA, GA

EDITED BY

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Introduction

These proceedings represent a sample of some of the excellent papers and posters presented at the 45th annual Computer Applications and Quantitative Methods in Archaeology (CAA) conference. This marked only the third time the CAAs had ventured across "The Pond" to the United States, and we think we were successful in attracting many first time CAA participants, which speaks to the vibrancy and relevance of the field. The week started with 12 workshops that covered a range of topics. The conference itself had over 350 papers and discussion sections along with over 20 posters spread across almost 40 sessions. These numbers also attest to the continued importance of the CAAs as a venue where cutting-edge ideas get shared. We experimented with novel session formats giving organizers options on how participants would share their research and interact. There were hybrid sessions with posters and discussions, as well as sessions like "Everything Wrong With…" that asked authors to contribute short, 10-minute papers, which then provided lengthier time for discussion. These accompanied more traditional session formats along with discussion sessions and roundtables.

The theme of the conference, as reflected in the title of this volume, was "Digital Archaeologies, Material Worlds (Past and Present)." We chose this theme to highlight the varying ways in which digital archaeologies are now practiced and how these practices are leading to new and exciting ways to share our data with interested publics. That diversity is reflected in the overarching themes we used to organize the papers in the conference and to structure the papers that make up this contribution. Those themes are 3D Acquisition – at the object level and the structure and site level, Broader View – Digital Archaeology and the Humanities, Collaborative Data Management, Critical Reflections, Education and Dissemination, Geographic Information Systems (GIS), Geophysics and Remote Sensing, Networks and Modeling, and Virtual Reality. The thematic focus on the present was also represented in a series of sessions focused on ethical issues, both as a field of practice and as an organization. These Critical Reflections are a sign of disciplinary maturity as we can turn our critical gaze on ourselves. There was a "Women in CAA" session, the first of its kind, as well as a "Decolonizing Digital Archaeology" session along with a discussion forum on a CAA Code of Conduct.

The conference started with an "ice-breaker" at the lovely Carlos Museum on Emory University's campus. On the way to Emory, everyone got to "enjoy" some of Atlanta's famous traffic, and although we arrived a bit late, everyone had time to explore the collections with the tasty snacks and cold beverages. On the first morning of the conference, we were treated to a keynote address by Dr. Ken Kvamme who provided his reflections on the historical trajectory of digital archaeology and where we, as practitioners, could grow as we move forward. The first full day of the conference ended with a poster session, that involved lively conversations fueled by some of Atlanta's finest local beers. While the temperatures outside were unseasonably cold, that did not stop folks from enjoying each other's company and the lunch options provided by local food trucks on Wednesday. Following the AGM was the conference dinner at Piedmont Park, Atlanta's version of New York City's Central Park. We had delicious BBQ (something us southerners pride ourselves on) and some traditional, Americana music. While there were not organized social events on Thursday, by that time people had learned their way around the city and were able to find warm spots to gather and continue the conversation after the conference had officially ended. While the conference was a blur for us, it was an honor to host everyone in our hometown, and we truly hope that everyone enjoyed themselves and took new ideas and new friends away with them from the conference.

Jeffrey B. Glover, Jessica Moss, and Dominique Rissolo

Acknowledgements

As we reflect back on the planning that led up to the conference, the work at the conference itself, and then the effort that has gone into getting these proceedings to press, it is a daunting task to try and thank everyone for the work they did in making all of this a success. We will try and do this roughly chronologically. The vetting of sessions and papers was a major task, and we owe a great debt to Paul Reilly and the other members of the CAA Scientific Committee. Glover and Reilly got to spend many an hour together on skype, which was an enjoyable unanticipated consequence of this process. A special thanks also goes to Hembo Pagi who helped with all things website-related, of which there were many. We are also indebted to Tommy Byrd for his expertise with Airtable and for automating the generation of a usable Conference Program.

A special thanks goes to members of the informal Conference Organizing / Advisory Committee. We did not get to thank y'all publicly at the conference, for which we apologize. Listed alphabetically, this group involved a mix of CAA "veterans" along with local colleagues: Michael Ashley, Geoff Avern, Robert Bryant, Jeff Clark, Lisa Fischer, Sarah Gale, Alan Greene, Ian Johnson, Scott Madry, Tim Murtha, Michael Page, Brian Seymore, and Tom Whitley. Special thanks go to Tom Whitley who helped plan and lead the coastal post-conference excursion and to Geoff Avern. Geoff gets special props for getting off a plane from Europe and going directly to the opening game of Atlanta United (our new soccer / football club) and then burning the midnight oil helping get things ready for the conference.

During the conference we would like to thank Jeannie Cho and the staff of the GSU Student Center for helping things run smoothly. We are also grateful for Elizabeth Horner and the folks at the Carlos Museum at Emory University for their help in organizing the "ice-breaker" event. Thanks to James Miles for dealing with the bursaries, which make such a big difference for our younger attendees. We are also grateful to Ken Kvamme for agreeing to deliver the keynote address. Along with the Georgia Coast post-conference excursion, we offered a one-day excursion to the Etowah Indian Mounds site north of Atlanta, and Adam King, by sharing his time and expertise, played a key role in making that a success.

When it comes to the publication of these proceedings, we first want to thank all of the authors for their patience and for the CAA members who did their reviews in a timely manner. This is not a simple or easy task. We are extremely grateful for the tireless work of Arianna Traviglia. We have also been assisted by a number of people at the University of Tübingen Library. Axel Braun helped us navigate the intricacies of OJS while Sandra Binder and Susanne Schmid have assisted greatly in getting these papers into their final shape as seen here.

We hope we have not forgotten anyone, but if we have, our apologies. We hope you enjoy the following papers and are inspired by the ideas presented here, and more importantly we hope you take that inspiration and share it with all of us at a future CAA conference.

GIS

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Antonin Nüsslein et al.
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To Boldly Go Where No One Has Gone Before: Integrating Site Location Analysis and Predictive Modelling, the Hierarchical Types Map

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Abstract

Over the years, predictive modelling has been characterized as being environmentally deterministic, a-temporal, or even as a way of 'effectively de-humanising the past'. Over the past ten years, however, spatial analysis of settlement patterns has progressed substantially, paying much more attention to the role of socio-cultural factors and the analysis of settlement pattern dynamics. In this paper, we will present an approach to site location analysis and predictive modelling that can be characterized as essentially data driven, yet is very much theoretically informed, and which has focused primarily on facilitating comparisons between various chrono-cultural contexts. Our experiments, that have been carried out since 2010, have mainly used data from the Roman period in various regions of France, but the general ideas and workflow can easily be transferred to other settings. To enrich the approach new developments were tested to understand the role of settlement hierarchy and its influence on the subsequent development and structuring of settlement patterns. These new developments were applied to three case study carried out in the north-east of France.

Keywords: site location analysis, predictive modelling, socio-cultural factors, temporal factors, Roman period

Introduction

In this paper, we present a new method to analyse the role of socio-environmental variables in rural settlement system development, with special emphasis on the role of the hierarchical structure of settlement. This method was developed as part of the PhD research conducted by the first author, in a case study for the Roman period in the Alsace-Lorraine region (NE France; Nüsslein 2018). This work is based on several research projects carried out in France between the 1980s and 2010s (Nuninger et al. 2012a; Favory, Nuninger & Sanders 2012; Nuninger, Sanders et al. 2006). The main interest of this long-term research is to study the dynamics of settlement systems and land use with a socio-environmental perspective and with a diachronic and transcultural comparison approach, in order to investigate the durability of the systems and the resilience of past societies.

This research started in the eastern Languedoc in the 1980s and was led by Jean-Luc Fiches, François Favory and Claude Raynaud (Fiches 1987; Favory 1989; Raynaud 1989; Favory and Fiches 1994; Favory et al. 1987; Favory, Ouriachi & Nuninger 2011). In the beginning of the 1990s two projects led by Sander van der Leeuw (Archaeomedes 1 and 2; Van der Leeuw 1998; Archaeomedes 1998; Van der Leeuw et al. 2003; Van der Leeuw et al. 2005) enlarged the regional focus to the Rhône valley, and initiated a partnership between French and Dutch scholars working on spatial analysis. Later on, within the framework of two other projects called Archaedyn 1 and 2 (led by François Favory and Laure Nuninger;

Favory et al. 2008, Nuninger et al. 2008; Gandini et al. 2008; Gandini, Favory & Nuninger 2012), researchers from Slovenia were associated and brought new case studies. Around 2010, a new collaboration was developed between the French and Dutch, called IHAPMA (Introducing the Human Factor in the Predictive Modelling for Archaeology), bringing in an additional case study in the Netherlands (Nuninger et al. 2012b; Verhagen et al. 2013a and b; Nuninger et al. 2016; Verhagen et al. 2016), and finally the Alsace-Lorraine region. An original methodology to study changes in the settlement system and land use was built step by step over all these projects. This has given us a common reference to perform interregional comparison on a solid basis (Favory, Nuninger & Sanders 2012).

In the IHAPMA project we were in particular interested in the estimation of human impact on rural settlement choices, and mainly for the Roman period.

The issue was to analyse changes in settlement location during the Roman period to better understand what drove the choices of past communities: the environmental conditions, the potential for movement or control, or socio-economic considerations - or all of them? In order to estimate the weight of each factor we combined the 'French' approach, mainly based on multivariate statistical analyses and classification, and the 'Dutch' approach, mainly based on predictive modelling methods. Predictive modelling is used here as a scientific tool to detect change from one period to another, and not for heritage management purposes (Nuninger et al. 2012b; Verhagen et al. 2013a).

In this project, we put special emphasis on socio-environmental variables, and it is the computation and analysis of one of these social variables that we will present in this paper: the hierarchical structure of the settlement systems.

This variable was originally defined by the Archaedyn team (Fovet in Nuninger et al. 2012c; Mathian and Tannier in Favory, Nuninger & Sanders 2012), but we adapted it to a raster environment and we developed the model as an operational GIS tool. It was then applied and analysed for the first time on three regional case studies in the Alsace-Lorraine region.

The Settlement of the Countryside Between Moselle and Rhine in the Roman Period

During Antiquity, the area between the Moselle and Rhine rivers was a region in which many historical events occurred (Gallic Wars, Germanic invasions, battles in Late Antiquity). These events successively changed its administrative and political organization. The main aim of the PhD research was to study, through spatial modelling and comparative approaches, the evolution of the settlement of micro-regions in a large and complex area between the 1st c. BC and the 5th c. AD.

The three study areas are located in Alsace and Lorraine (Figure 1). Two are located on the Plateau Lorrain (zone 1 "Entre Alsace Bossue et Pays de Bitche", zone 2 "Entre Seille et Nied") and one in the Plaine d'Alsace (zone 3 "Basse vallée de la Bruche"). They are well known by survey and excavations. Their size varies between 300 and 600 km². All of them were more or less systematically surveyed by field walking and in addition about 10 to 15% of the sites were excavated. The number of Roman settlements per zone varies from 65 to more than 300 and at least 30% can be dated at the century scale.

These sites are not all the same: their size varies between 100 m² and 100 ha, and their wealth and longevity are very variable. Based on these observations, we can assume different functional roles of the settlements within the system. This is why a hierarchic-functional typology of the settlements was created, based on the method developed in the Archaeomedes and Archaedyn projects, using a combination of correspondence analysis and hierarchical clustering (Van der Leeuw et al. 2003; Favory et al. 1999; Bertoncello et al. 2012a). "The principle is that of a convergence of multiple indices whose combination makes sense in the a posteriori interpretation by the archaeologist and allows him to identify a typological-functional hierarchy" (Favory, Nuninger & Sanders 2012). This analysis resulted in 9 different, hierarchic-functional classes of settlements, depending on several variables but in particular the surface area of the settlement, its duration of life, and the quality of the material used for construction (Figure 2 and Table 1). The settlements are thus classified into hierar-

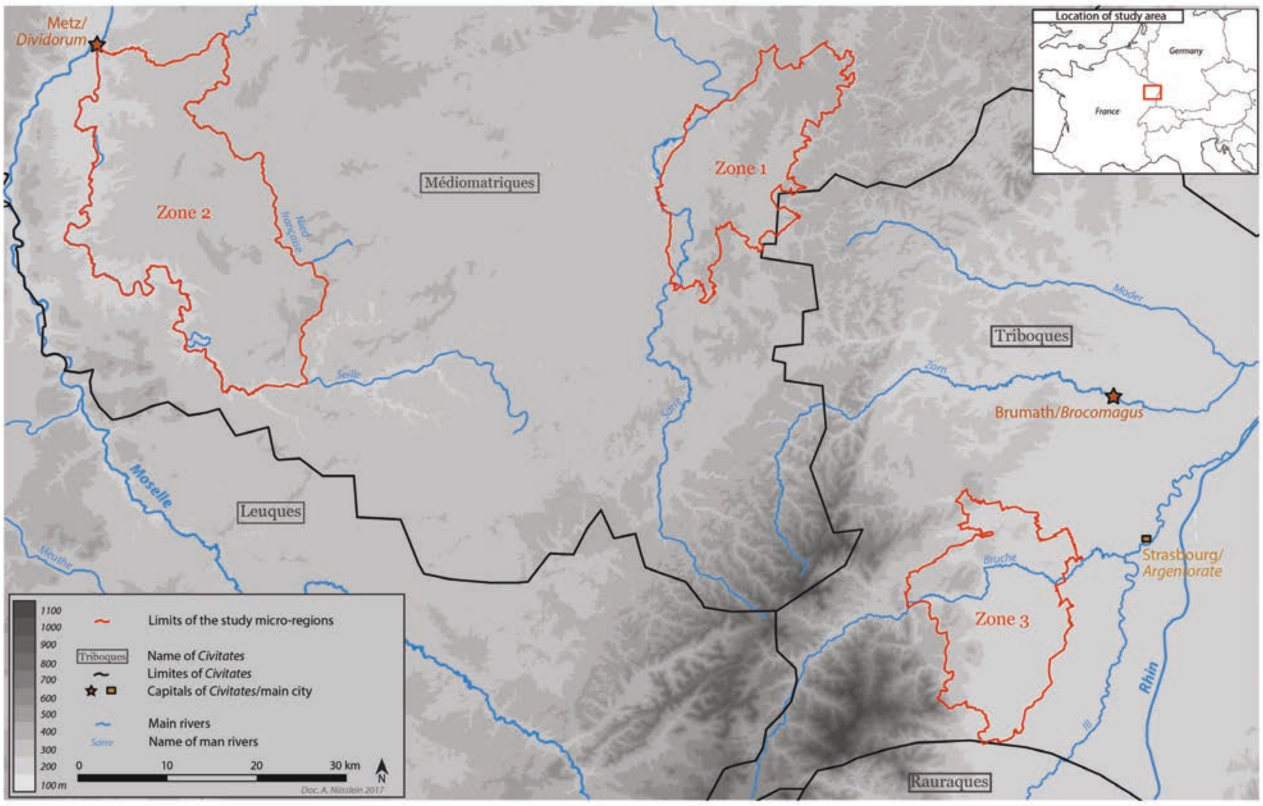


Figure 1. Map of the study areas in Alsace and Lorraine.

chically ranked groups of settlements that can be interpreted from agglomerations to small farms. When we analyse the sites according to this classification, we can see that the micro-regions have very different settlement compositions. In zones 1 and 2, the habitats are mainly isolated (villas and farms) whereas in zone 3 the habitats are mainly grouped (villages and hamlets).

	Variables
A	Area
B	Materials used for the construction (wood, stone, mortar, etc.)
C	Level of conveniences (presence of hypocauste, bath, etc.)
D	Diversity of ceramic artefacts
E	Other artefacts (iron, silver, tools, etc.)
F	Craft activities
G	Duration of life span
H	Date of creation of the settlement

Table 1. Variables used to create the hierarchic-functional typology of the settlements (Nüsslein 2018).

However, as mentioned by Favory, Nuninger & Sanders (2012), it should be noted that these are "properties associated with the settlement referring to various periods" and no time variable is taken into account in the analysis. "Thus the existence of entities refers to an abstract a-temporal level" and does not illustrate the internal evolution of habitats. Indeed, the excavations show that the studied habitats sometimes follow long development trajectories in which they move up in the hierarchical ranking, and then decline (Nüsslein 2016). Moreover, some sites of similar status at the beginning of the Roman period will develop more strongly than their neighbours. What are the local factors explaining these different phenomena?

After this step of classification and site study, the structuring spaces generated by the sites were studied using a number of statistical and geospatial tools (for example: density, dispersion/concentration, distances between sites, etc.). These analyses showed that the areas presented clear differences in occupation over the centuries. The second question then is: what type of socio-environmental factors can explain these variations in time and space?

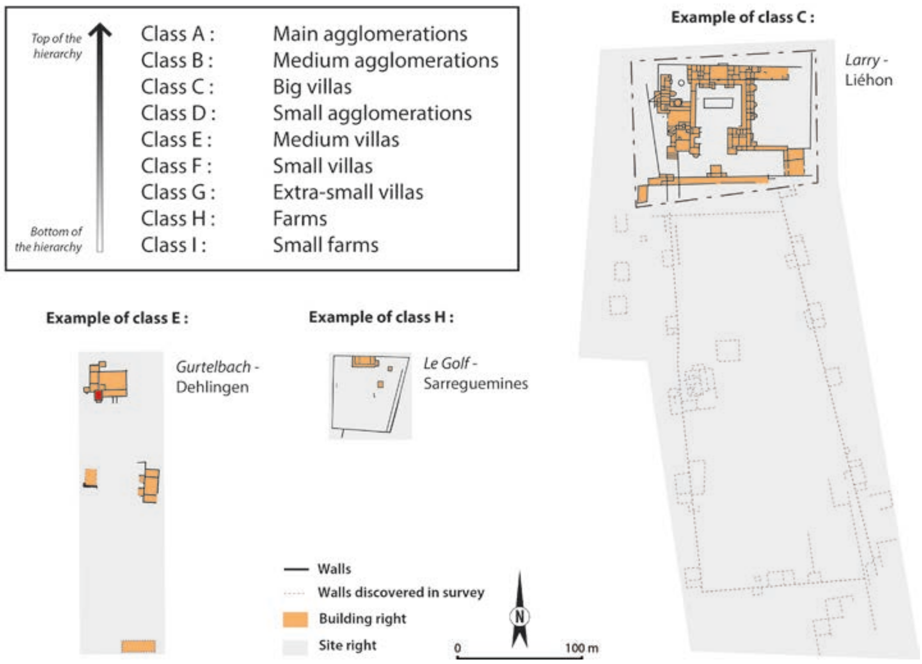


Figure 2. Typological-functional hierarchy of the settlements.

To answer these two questions, the local conditions of settlement creation were studied based on the variables developed in the previous studies cited and focusing, in particular, on the relationship between settlements according to their rank within a spatial and dynamical perspective. For this, a new tool was developed in a GIS environment so as to compute a raster map of the hierarchic-functional structure of the settlement system.

The Map of Hierarchic-Functional Structure of the Settlement System

The Original Concept

In the different cases studied in the previous projects, it was observed that different types of settlements are often spatially associated (Favory et al. 1994; Favory et al. in Archaeomedes 1998; Nuninger et al. 2006; Bertoncello et al. 2012a and 2012b). The issue was how to qualify, with a synthetic index, the neighbourhood of a location according to its potential in terms of territorial organization.

There are many different types of hierarchical-functional assemblages, consisting of multiple, interacting occupations. Based on these observations, the Archaedyn and the IHAPMA teams suggested further analysis by characterizing each portion of space (place, grid cell) by quantitatively describing its neighbourhood using a set of environmental and archaeological attributes. Among the archaeological variables, we will illustrate the "heritage" index and the "hierarchical-functional structure" index.

The first one is based on the concept of "neighbourhood legacy", characterizing the accumulated investment in the landscape at a time t. It gives the possibility to compute heritage maps where each cell gets a value calculated by the accumulated length of occupation in the neighbourhood at a time t, weighted by temporal and spatial distance (Favory, Nuninger & Sanders 2012; Nuninger et al. 2016; Verhagen et al. 2016).

In parallel, and based on the same idea of characterizing the social context, Élise Fovet suggested to identify the level of "hierarchical organization" of the settlement pattern within clusters of settlements defined by a segmentation of the space based on a density map (see Nuninger et al. 2012c; Bertoncello et al. 2012a).

In order to determine the level of hierarchical organization of settlement within each sector, two indicators were calculated:

1. The hierarchical variety of the settlements which shows the degree of diversification of the settlement types (number of different classes) and

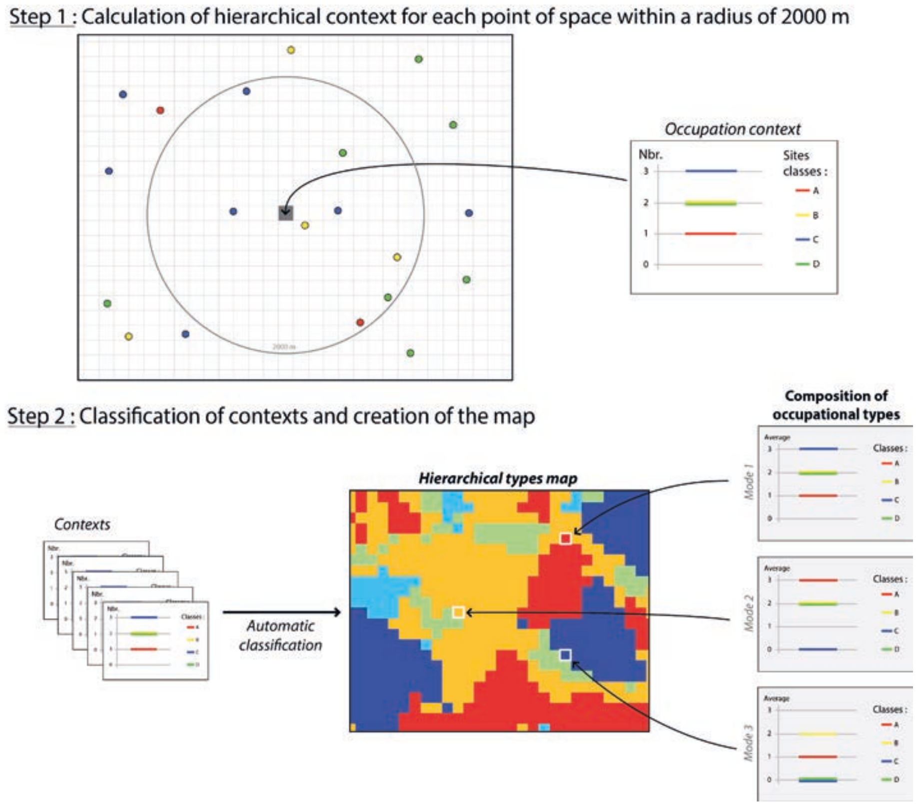


Figure 3. Protocol for the map of hierarchic-functional structure of the settlement system.

2. The differentiation of the classes present in each sector based on standard deviation.

For an equivalent value of the variety, we can distinguish:

a. a low range—i.e., a high homogeneity—which indicates the association of settlements belonging to hierarchically close classes (e.g., classes 1 and 2, or classes 5 and 6),

b. a high range or a strong differentiation when classes are extreme (e.g., classes 1 and 6).

Then both indicators were combined so as to indicate the degree of settlement organization within a sector, i.-e., the value of the “hierarchical-functional structure. It makes it possible to distinguish poorly structured sectors (non-diversified settlement types with similar hierarchical levels) from highly structured sectors (highly diversified and exhibiting a broad spectrum of settlement classes, see Figure 4).

In this approach, the result is largely dependent on the identified aggregates or sectors used for the analysis and the solution adopted remains problematic with respect to monitoring regional comparison. To overcome this problem, Hélène Mathian and Cécile Tannier (see Favory, Nuninger & Sanders 2012) proposed to compute a value based on a neighbourhood analysis using a regular point cloud and taking account of the hierarchical ranking of the settlements. Thus the distance to the closest neighbours of the settlement was calculated according to their hierarchical level. As a result, the potential of a place n can be defined with respect to the structuring level of the settlement system that surrounds it at a time t, using the same index created previously by Fovet. This approach takes into account the entire spatial region studied rather than just its occupied area, including the marginal or totally abandoned areas, which help us understand the types of land use and the organization of the settlement systems.

While the concept and the general method were already designed to determine systematically the value of the hierarchical-functional structure within a study area, its application within a GIS environment remained to be developed. This new step was the work done within the PhD of the first author who adapted the method and developed a tool for Arc-

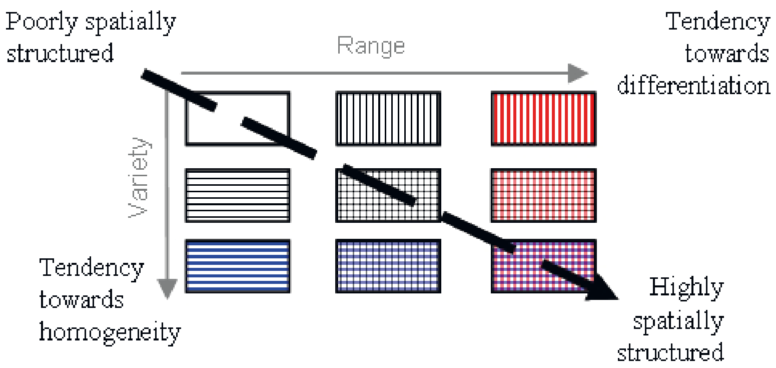
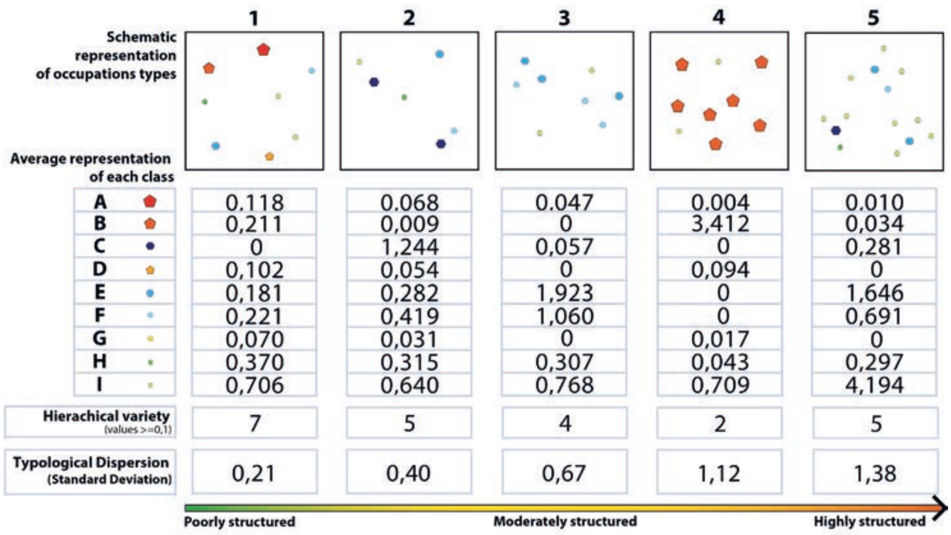


Figure 4. Different combinations of the indices of hierarchical variety and range showing different levels of hierarchical organization of settlement patterns (after Fovet in Nuninger et al. 2012c).



	1	2	3	4	5
A	0.118	0.068	0.047	0.004	0.010
B	0,211	0,009	0	3,412	0,034
C	0	1,244	0,057	0	0,281
D	0,102	0,054	0	0,094	0
E	0,181	0,282	1,923	0	1,646
F	0,221	0,419	1,060	0	0,691
G	0,070	0,031	0	0,017	0
H	0,370	0,315	0,307	0,043	0,297
I	0,706	0,640	0,768	0,709	4,194
Hierachical variety (values >=0,1)	7	5	4	2	5
Typological Dispersion (Standard Deviation)	0,21	0,40	0,67	1,12	1,38

Figure 5. Categories of the hierarchical-functional contexts, ranked from 1 to 5.

GIS. This tool was then used in three regional case studies for comparison.

Creating the Map of Hierarchical-Functional Structure

To create the maps, Nüsslein (2018) used a hierarchical-functional typology and a contextual approach. Compared to the method developed by Mathian and Tannier, the approach differs in two major points: 1- instead of a point cloud, a raster environment was used to calculate the value of the "hierarchical-functional structure" and 2- the choice of the radius was not based on nearest neighbours analysis, but was decided after testing a series of radii using the method developed by François-Pierre Tourneux (Tourneux 2000; Nuninger et al. 2012b; Verhagen et al. 2013a).

For each cell in space, the hierarchical context that develops there is established. This "context" is representing the profile of one cell according to the assemblage of settlements surrounding this cell (Figure 3, step 1). To define the size and morphology of the "surroundings", we chose to use a 2000 m radius around each cell. The size of the radius was fixed according to its statistical significance to get enough variability locally and regionally. Once all the "contexts" were computed for each cell in each micro-region, we obtained a series of profiles describing the cells in the same way in the three case studies (Figure 3, step 2, a). An automatic k-means classification was then performed on the whole set of cells to group those with similar context profiles together. The result of the classification makes it possible to distinguish five main context categories (Figure 3, step 2). The results of this new classification were then mapped (Figure 3, step 2). Each cell on the raster map indicates the presence of each category of the hierarchical-functional contexts, which refers to what we call the "hierarchical type of context". According to the assumption that a settlement

Categories ranked by their level of hierarchical organization	Interpretation
Level 1	This type represents a settlement system with a high hierarchical variety but with a low typological dispersion. This type thus presents a low level of structuring.
Level 2	This type, which has a medium level of structuring, displays a moderately varied assemblage and an average typological dispersion. Observing the spatial configuration of this type, we can see that these are large isolated villas or small aggregates, composed of a large villa and one or two small settlements in the periphery.
Level 3	Dense settlement but not very varied, showing an average typological dispersion. This assemblage, with a level of structuration comparable to the previous type, is composed of small aggregates mixing small and medium-sized villas accompanied sometimes by small farms.
Level 4	This settlement system has a medium level of structuring and is not very varied, but there is a very strong typological dispersion. This assembly is composed of medium-sized agglomerations around which sometimes gravitate some small farms.
Level 5	These are the most structured and most complex settlement systems. The settlement is varied and the hierarchical dispersion is very strong: the gap between small and large habitats is important but includes intermediate sites. Morphologically, this type shows small sets whose main settlements are large and medium-sized villas, around which gravitate many farms and small villas.

Table 2. Categories of the hierarchical-functional context ranked according to their level of hierarchical organization, from unstructured to very structured.

can interact with its neighbors, we can assume a sort of complementarity between settlements of the same hierarchical-functional rank and between various ranks. Based on this hypothesis, when considering the choice of a place to settle or the potential of development for a new occupation, it could logically be presumed that the hierarchical type of context is a variable playing a role. In other words, according to its hierarchical type of context a portion of space (cell) will presumably be more or less attractive to settle.

In order to qualify the attractiveness, the statistical composition of each category of the hierarchical-functional context on the map (Figure 3 step 2, b) was analysed in order to interpret their level of hierarchical organization. As in the method developed by the ArchaeDyn collective for each category, we computed the two indicators: the hierarchical variety of the settlement and the range based on standard deviation. The level of hierarchical organization for each category was then defined by the combination of both indicators (Figure 4). We estimate that the more a type contains various types of settlement, and the larger its typological dispersion, the higher its level of organization.

Each category of the hierarchical-functional context was then ranked from 1 to 5 according to their level of hierarchical organization, from an unstructured to a very structured social landscape (Table 1 and Figure 5).

Integrating the Factors in Site Location Analysis and Predictive Modelling

In order to analyse the potential attractiveness of each cell according to the level of hierarchical organization in its surrounding, we used a predictive model based on χ^2-tests and relative gain calculations developed in previous works (Wansleeben and Verhart 1992; Verhagen 2007). This analysis aimed to see if any significant site location preferences could be established and how strong the preferences are. The predictive values were computed for periods of one century. For each century n, the model looked at the location of new settlements according to the pre-existent hierarchical context in century n - 1. For example, the predictive value of new site locations for the 2nd c. AD is calculated using the category of the hierarchical-functional context of the 1st c. AD. The analysis was done for 1st to 4th c. AD, the periods for which sufficient sites were available for quantitative analysis.

Categories of geo-environ-mental context (topography)	Interpretation
1	South to east aspect, very warm to warm environment with medium (4-8%) to steep (8-15%) slopes.
2	South to west aspect, warm to medium-fresh environment with flat area (à-2%) or weak slopes (2-4%)
3	West aspect, warm to fresh environment with medium to steep slopes. This context is marked by a strong mix of criteria
4	No or north to east aspect, medium-warm to medium-fresh environment with flat areas
5	North to east aspect, fresh to medium-warm environment with flat area to medium slopes. This context is marked by a strong mix of criteria
6	North to east aspect, cold to fresh environment with medium to steep slopes.

Table 3. Categories of geo-environmental context.

To estimate the importance of this social factor against the topographical one in the evolution of site location preferences, the predictive values were also computed for the geo-environmental context. The methodology used was exactly the same as the one developed in previous work by the IHAPMA team (Nuninger et al. 2012b; Verhagen et al. 2013a). The geo-environmental context is based on three groups of variables (slope, aspect and solar radiation) computed using the IGN DTM with a resolution of 50m. For solar radiation the qualitative value from cold to very warm is determined according to the medium value of the theoretical solar radiation per year calculated on the three micro-regions. The extent of the context was defined by an appropriate radius, which provided the most statistical contrast in the context profiles. The geo-environmental context profile was calculated for each cell in each region. Then, a Principal Component Analysis (PCA) followed by a Maximum Likelihood Classification were done on the whole cells giving a final map with six categories of geo-environmental contexts (Table 3).

Results

The Map of Hierarchical-Functional Structure

Before integrating the geo-environmental variable in site location analysis, we would like to comment on the evolution of hierarchical organization and the differences observed between the study areas.

In the 1st c. BC, space is sparsely occupied in all study regions. However, the intensity of occupation is high around the main settlements (Nüsslein 2018), such as the villas in zone 1 and 2 (in reality, these sites are still farms at this period). The maps show that the sectors where level 1 (Table 2) is developing dominate in all micro-regions. The spaces still have a low level of hierarchical organization. Globally, for all the micro-regions, in this century the most important sites are established, from which settlement will intensify and expand, in the most structured sector.

In the 1st c. AD, occupation becomes more intense (Figure 6). The main settlements are expanding in space. In all micro-regions, level 1 still dominates, but weakens in favour of more structured assemblages. It is now confined to the newly settled peripheral spaces. Level 3 becomes most important. In the zones 1 and 2 the assemblages that combine medium and small villa type of settlements take up more place in the centre of the areas previously occupied, thanks in particular to the densification of settlement. The settlement system appears to become more complex. In zones 1 and 2, the densification of space also allows the emergence of level 5, the most organized. Its extent is still very limited but it will increase in the next centuries. This level of hierarchical organization appears in an area where a highly structured set of villas and small farms is developing.

In the 2nd c. AD, the settlement system is very dynamic, and small settlements appear in the surroundings where the main settlements are located. They are

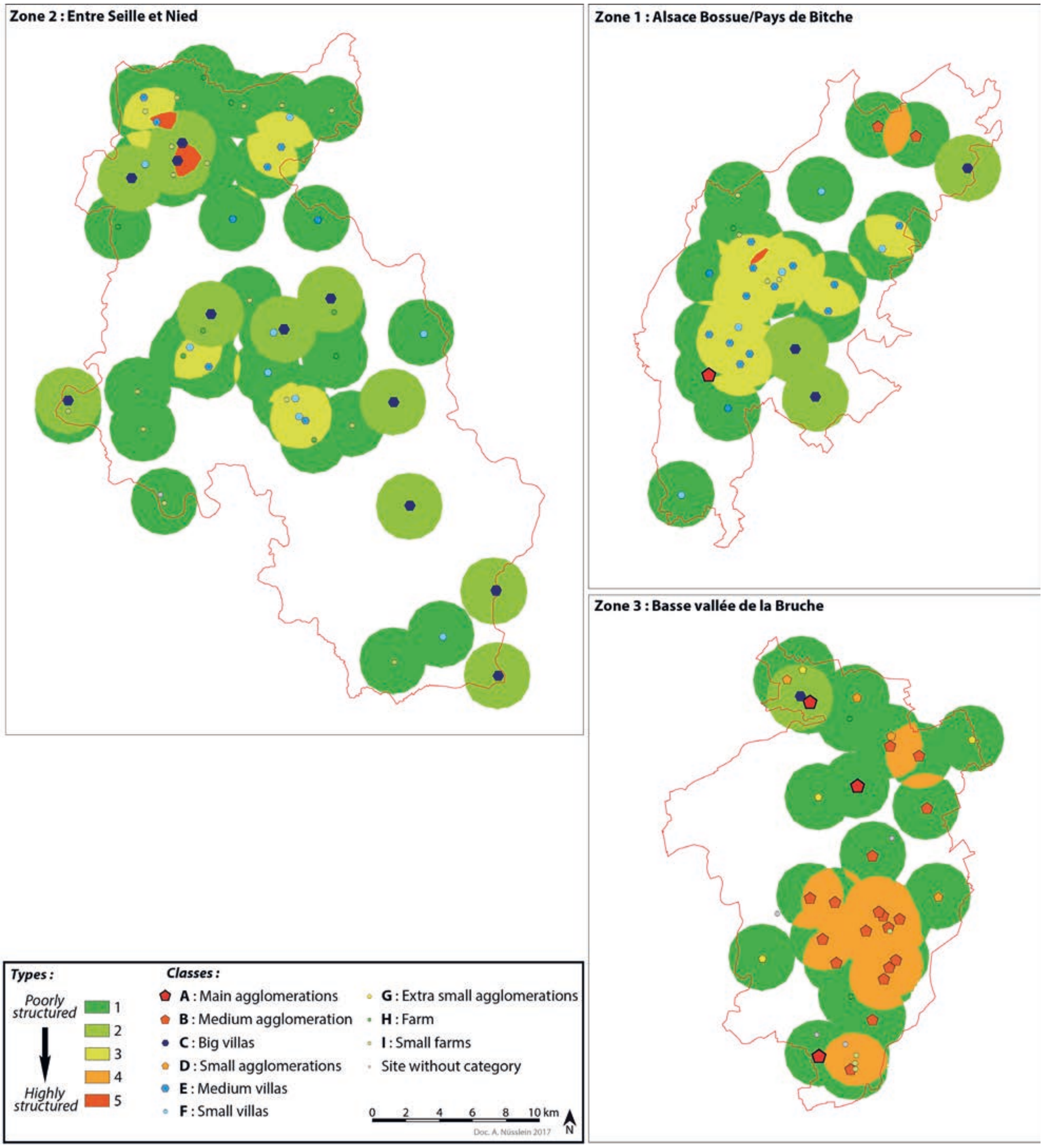


Figure 6. Maps of the hierarchical-functional structure for the 1st century AD.

founded in close proximity to the larger ones and increase the intensity of occupation in many parts of the space. Concerning the hierarchical organization of spaces, the configuration changes strongly in the zone 1 and 2 where the settlement pattern seems to become more complex and the main habitats develop. The increased density of population there leads to an increase in the level of organization. Concretely, on the maps, this phenomenon is illustrated by the increase in the number of contexts occupied by level 3 and 5, which appear in sectors formerly characterized by level 1 and 2.

During the 3rd c. AD, the hierarchical structure of the spaces remains stable in zones 1 and 3 (Figure 7). In zone 2, the situation seems to evolve in the 3rd century. It shows a decrease in the representation of level 1 in favour of level 3. This evolution is due to the abandonment of certain isolated peripheral

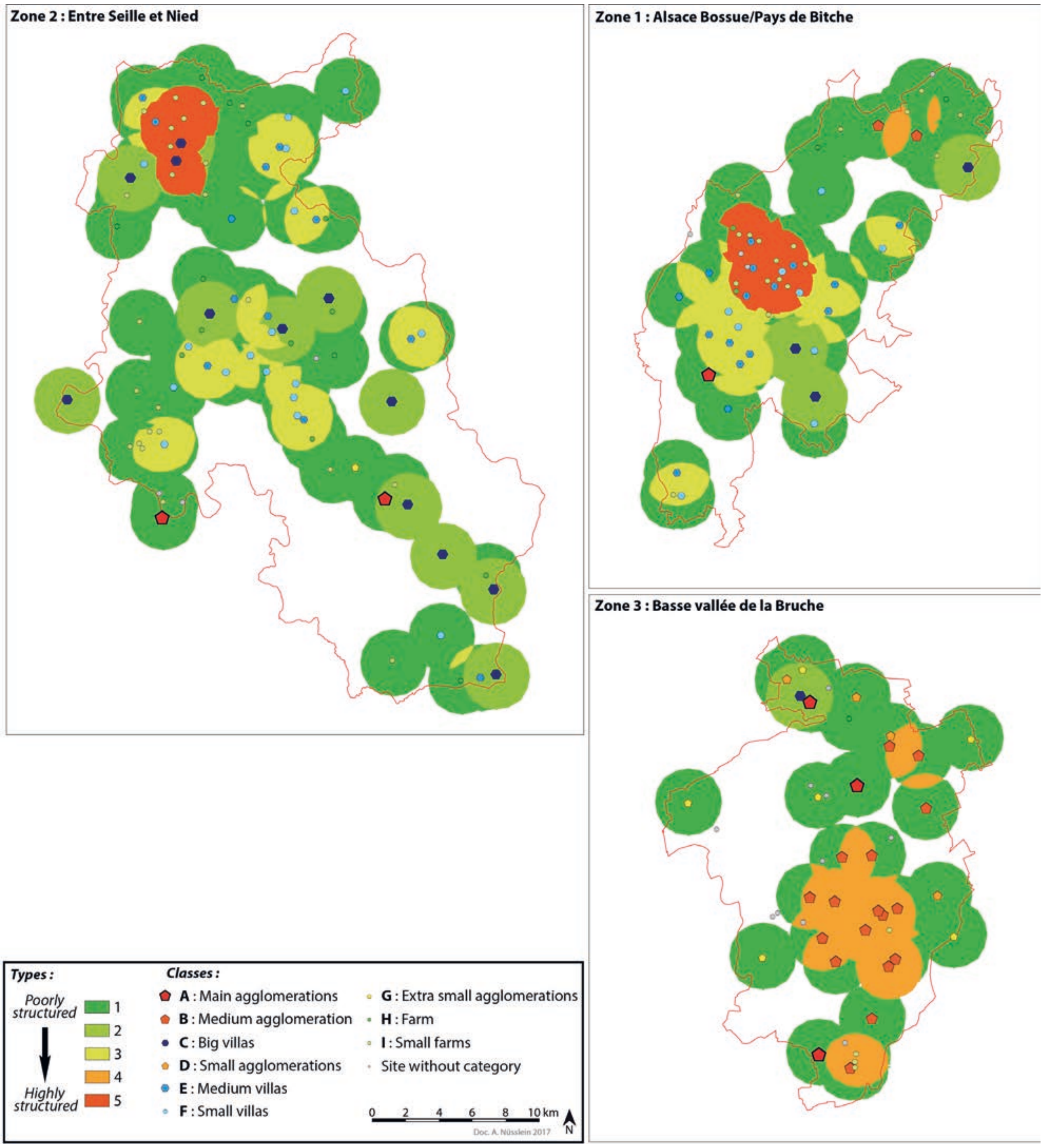


Figure 7. Maps of the hierarchical-functional structure for the 3rd century AD.

habitats but also to the densification of sectors already occupied where they are set up. New small sets emerge, composed of small and medium-sized villas. The process of increasing the level of structuring of the settlement, which seems already to have been accomplished in zones 1 and 3, thus seems to continue in zone 2. Finally, note that where occupation is most intense, the level of hierarchical organization is high.

In the 4th c. AD, settlement systems change with an apparent decrease (Figure 8). The peripheral spaces are abandoned and the most intensively exploited and structured sectors are abandoned. However, some densely occupied areas, where large habitats are located, remain busy. Maps of the hierarchical-functional structure of the settlement system, show that overall, in all micro-regions, the settlement system apparently becomes less complex and the level of structuring of the spaces diminishes.

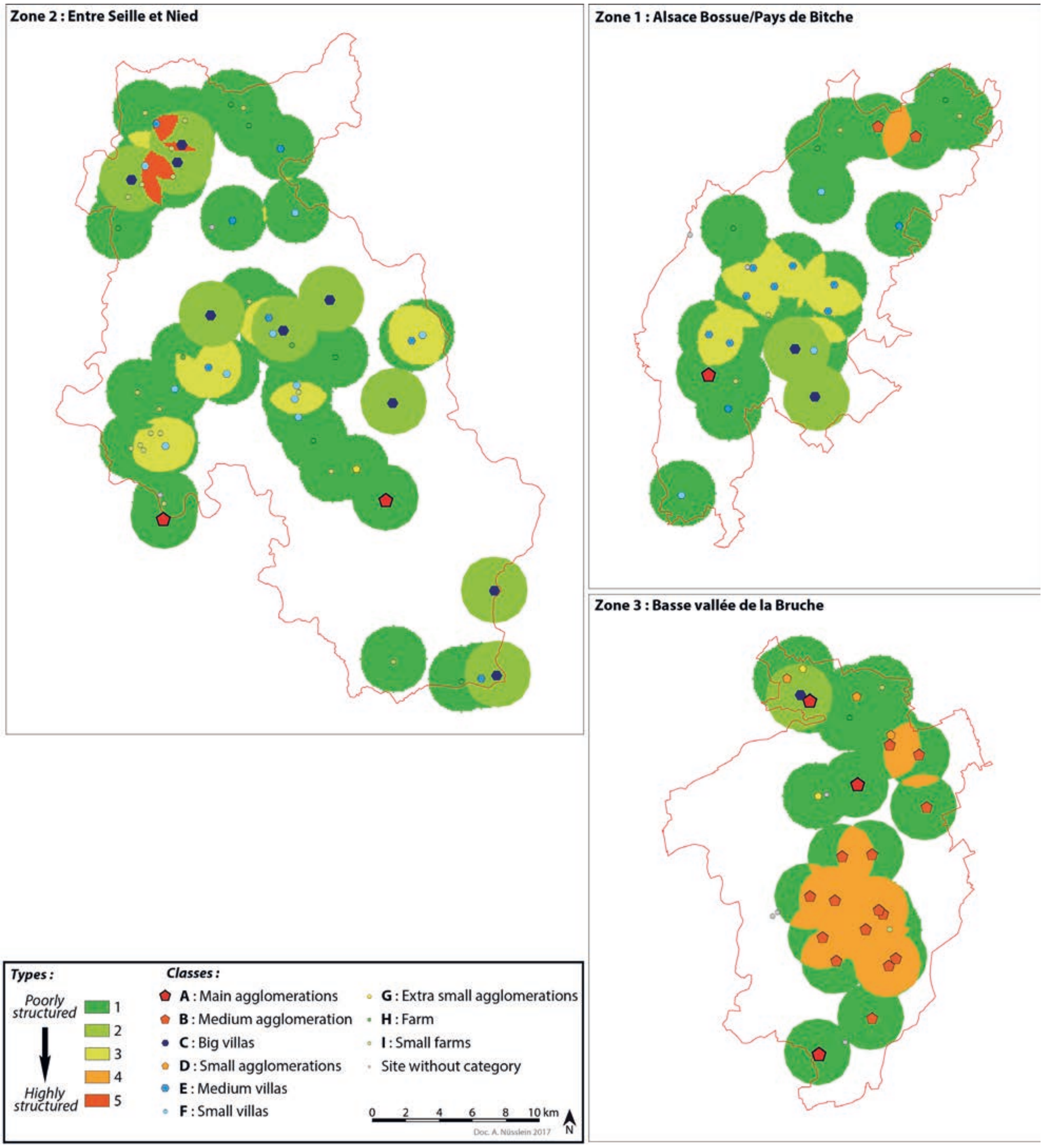


Figure 8. Maps of the hierarchical-functional structure for the 4th century AD.

However, where large villas subsist, the settlement seems to resist better.

Results of Site Location Analysis and Predictive Modelling Using Geo-Environmental Factors

In order to test the relevance of this variable and to see its importance, we first apply the protocol only with geo-environmental factors. The classification is composed of six classes of environmental contexts, ordered from 'warm' to 'cold' (Table 3, Figure 9). Here we present only the results for the three micro-regions presented in this paper. The comparisons are based on an analysis of the full dataset, so including both existing and new settlements.

For zone 1, the model has a low maximum relative gain for all settlements dated in Antiquity (= the whole Roman period; 7.2%). Thus, there is no evidence of geo-environmental determinism according to this index. Indeed, we observe that there are no really attractive or repulsive contexts. However, for settlements dated per century, the model presents better predictive values than for all settlements, but the maximum gain values remain low. Overall, it is interesting to note that the evolution of the maximum gain shows that when the population increases, the spatial distribution of habitats in the contexts becomes more homogeneous and when the numbers decrease, the differences become more significant. The model presents a higher predictive value for all settlements from Antiquity in zone 2 than in zone 1. The choice is more pronounced. This sector also has a different geo-environmental profile from the other micro-regions. This illustrates the existence of different strategies in the two micro-regions. In zone 3, the model has a greater maximum relative gain than recorded in the other micro-regions for all settlements dating in Antiquity (23.6%). Apart from the fact that context 2 is the most attractive one during almost the whole of Antiquity, the strategy adopted by the settlements of this zone is different from what was observed for the other micro-regions. The choices here are more marked and remain virtually the same throughout the period studied. Despite the increase or decrease in the number of establishments, the predictive values do not change and the preferentially exploited environments remain the same.

To conclude, we can see that the model based on geo-environmental factors has a low predictive value for two of the three micro-regions. It does not show a very clear influence of geo-environmental factors for site location in the Roman period, which confirms the results obtained in our earlier studies (Nuninger et al. 2012b).

Results with the Map of Hierarchical Structure

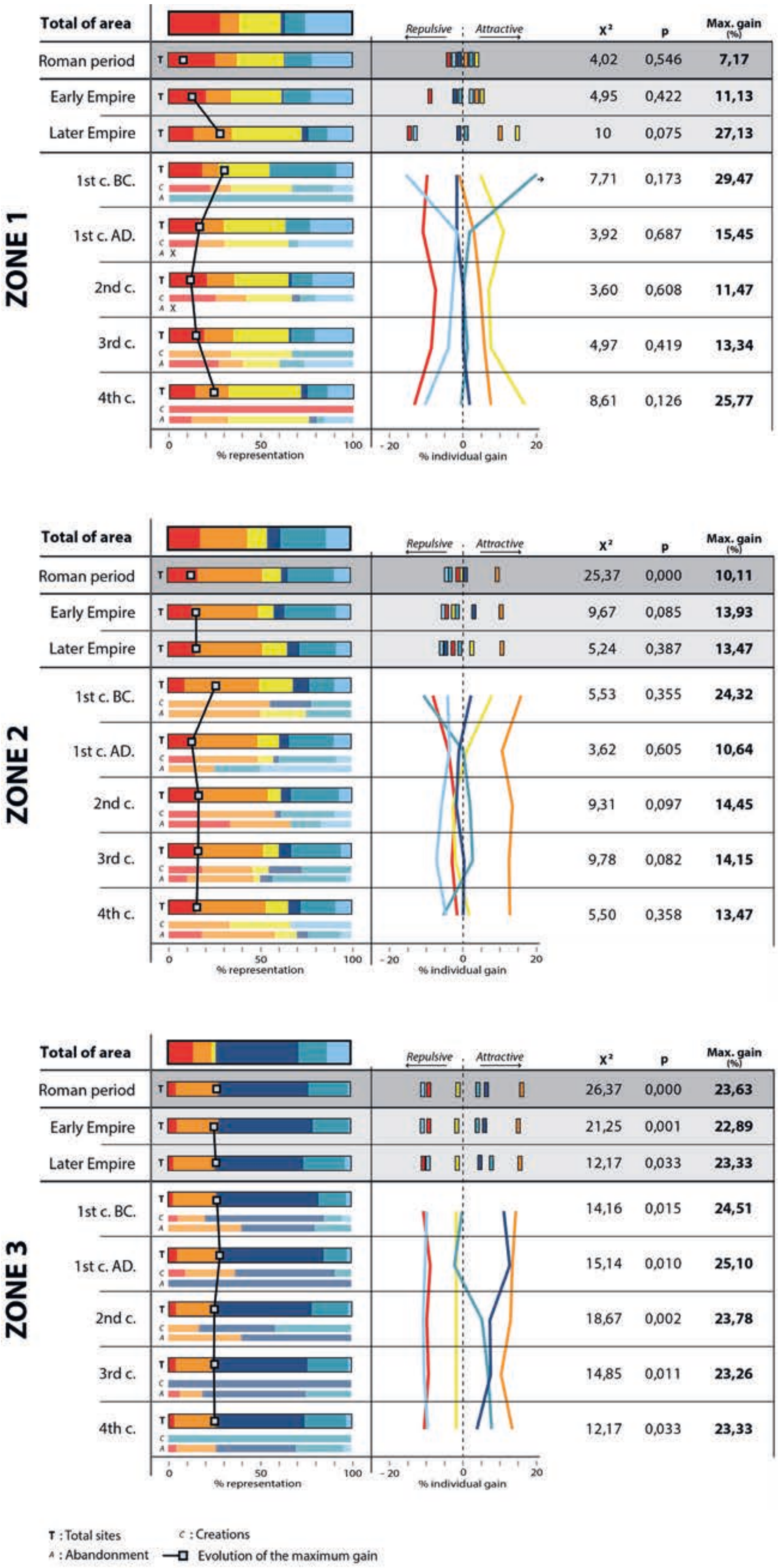
Next, we applied the protocol for the variable 'hierarchical structure' (Figure 10). Here, the comparisons are based on an analysis of the newly created settlements.

In micro-region 1, in the 1st c. AD, the settlements are established in the areas previously occupied by types 1 and 3. In the 2nd century there is an increase in the maximum relative gain. This is due to the fact that a large number of new sites are established in an environment that is moderately structured (type 3) and which becomes very attractive. In the 3rd century the choices become even more pronounced as the most structured spaces (type 5) are preferred. Overall, structured occupancy types (types 5 and 3) are more attractive than contexts with low levels of structuring (types 1 and 2). In the next century, the situation is somewhat balanced because of the numerous abandonments that occur in types 3 and 5. The sectors occupied by these two types are nevertheless more attractive than the other categories.

In zone 2, at the beginning of Antiquity, the areas characterized by moderately structured contexts attract most settlements (types 2 and 3). In the 2nd c. AD, the maximum relative gain is increasing, and new settlements always favour contexts that were weakly to moderately structured in the previous century. In the 3rd century, contrary to what can be observed in zone 1, the settlements do not necessarily prefer a location in the sectors that were most hierarchical in the previous century. In the following period, the situation changes little. Nevertheless, the less hierarchical contexts are now less attractive, the settlements preferring to remain in environments characterized by types 3 and 5.

In zone 3 in the 1st c. AD, new settlements are predominantly found in contexts that do not have the highest structuring values (types 1 and 2). The most attractive category nevertheless gathers contexts of type 4. In the next century, the less structured environments of type 1 become repulsive. During the 3rd century, type 4 decreases but the situation is not changing very much. However, in the 4th century, the maximum relative gain increases because of numerous abandonments in the zones with type 1. Habitats thus refocus in contexts that are most structured.

To conclude, these analyses clearly confirm the importance of this variable that has strong predictive power. There are also differences between micro-regions and types of hierarchical structuration. In zone 1, the structured sectors strongly attract settlement in the early Roman period. This attraction becomes less marked later and the situation tends to balance. In zone 2, the choices are less pronounced, and it is found that the settlements located in the most structured areas, that is, the areas dominated by the main



Contexts classification

Type	1	2	3	4	5	6
Aspect	South to east	South to west	West	Flat, north, east	Nord to east	North to east
Solar radiation	Very hot to hot	Hot to cold	Hot to cold	Hot to cold	Cold	Cold to very cold
Slope	Medium to steep	Low to flat	Medium to steep	Flat	Medium to flat	Steep to medium
Mixit context	Low	Low	High	Low	High	Low

Figure 9. Results for the geo-environmental factors.

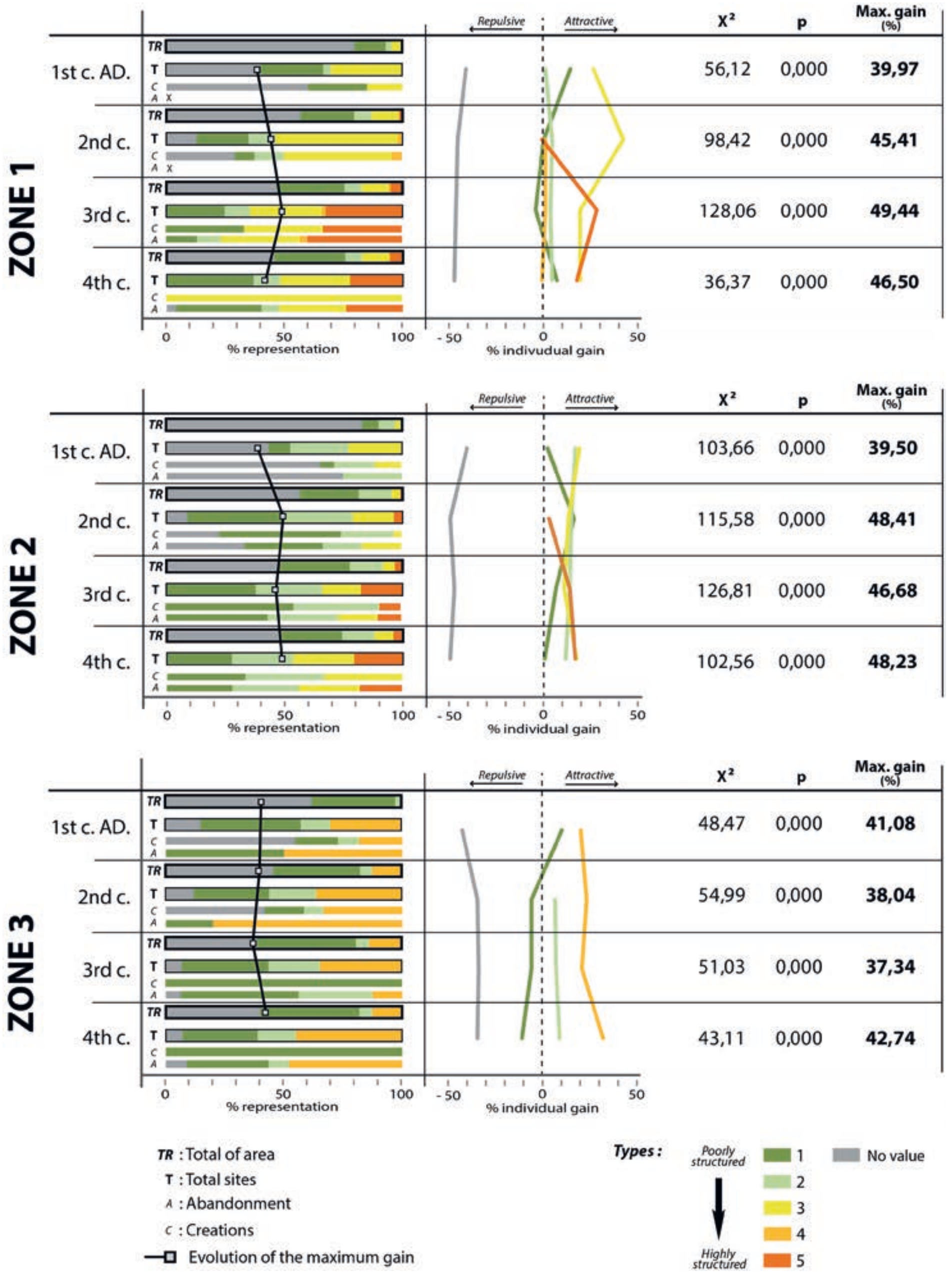


Figure 10. Results for the socio-environmental factors based on the map of the hierarchic-functional structure.

settlements, are more resistant during Late Antiquity. In zone 3, settlements favour an establishment on the most structured forms of occupation, throughout the whole of the Roman period.

It should also be noted that this variable seems to play an important role in the internal development of sites. Indeed, we have seen from other analyses that the sites, installed at the beginning of the Roman period and which will later find themselves in a structured hierarchical context, will evolve more strongly.

Conversely, small sites that set up later in such context will evolve very little, but they will be more sustainable.

Conclusion

The results of this research highlight the diversity of habitat types, spatial patterns and dynamics between Rhine and Moselle during the Roman Period. The study clearly shows that socio-environmental parameters have a very important influence on the trajectory of sites and on the development of the settlement patterns.

More generally, the study presented in this paper shows the importance of taking socio-environmental variables into account in site location analysis, the development of the sites studies, and predictive modelling studies.

We want to emphasize, and this is one of the key elements we have highlighted in this study, that the evolution of settlements patterns depends not only on geo-environmental conditions, but that socio-environmental parameters have a very important influence on the societies we are studying. Concerning the way forward, we believe that the variable "map of hierarchical structure" can be further improved and made more efficient. A next step is to integrate this variable directly with other geo-environmental and socio-cultural parameters in site location analysis.

For the moment, this study confirms the interest of predictive modelling tools to approach the complexity of settlement system trajectories. The method allows for diachronic and regional comparisons, but we have to test it at a larger level on many case studies.

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Display Matters? Enhanced Visualisation of Norwegian Neolithic Landscapes

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Abstract

The paper explores enhanced visualisation of site distribution, with the purpose of understanding shifts in landscape preferences from Middle to Late Neolithic in East Norway. It includes single finds and artefacts from excavations, and the criteria are spatiotemporal accuracy related to the scale of analysis. The representativity of the dataset is evaluated. The artefacts are seen as a Poincaré set that describes the nonlinear system of movement and tasks in the prehistoric landscape. This gives a different approach to the study of site distributions that are results of single events performed in a continuous time and space. This Poincaré set is visualised as find densities in landscape subregions. Archaeological periods are used as temporal scale levels, while landscape subregions, defined through a holistic landscape categorisation, are applied as the spatial scale level.

Keywords: landscape categorisation, taskscape, nonlinear systems, MUSIT database, map-based EDA

Introduction

This study is an extension of the project Dynamic Distributions (Matsumoto and Uleberg 2015a; Uleberg and Matsumoto 2015; Uleberg and Matsumoto 2016), which investigated changing relations between humans and landscape during the Stone Age in East Norway. The elements in the analysis are archaeological single finds and landscape regions. The lithic finds are from the collection at the Museum of Cultural History (Kulturhistorisk Museum, hereafter KHM) at the University of Oslo. The datasets are published through MUSIT (MUSeum IT), at www.unimus.no. The landscape regions are based on a holistic landscape categorisation (Puschmann 1998).

Dynamic Distributions analysed the find distribution at different temporal and spatial scales. The scales correlated with different spatiotemporal aggregations of archaeological material projected onto varying aggregations of landscape regions. The site distribution visualised changes in landscape preferences over time. This combination of archaeological single finds with varying aggregations of landscape regions has contributed to a different approach to archaeological distribution maps.

The present article extends the analyses from Dynamic Distributions by focusing on sites as well as single finds dated to the Middle and Late Neolithic from seven counties in East Norway (Figure 1). The sites and single finds are results of events that took place in a time–space continuum, and are analysed as a 3D Poincaré set (Uleberg 2004). The points in this set are aggregated and visualised as distributions in the holistically defined landscape regions (Puschmann 1998).

The MUSIT Database

The current analysis is based on KHM's open data published through MUSIT, which is a cooperative initiative created by the Norwegian university museums (Matsumoto and Uleberg 2015a; Uleberg and Matsumoto 2009). The MUSIT database is event

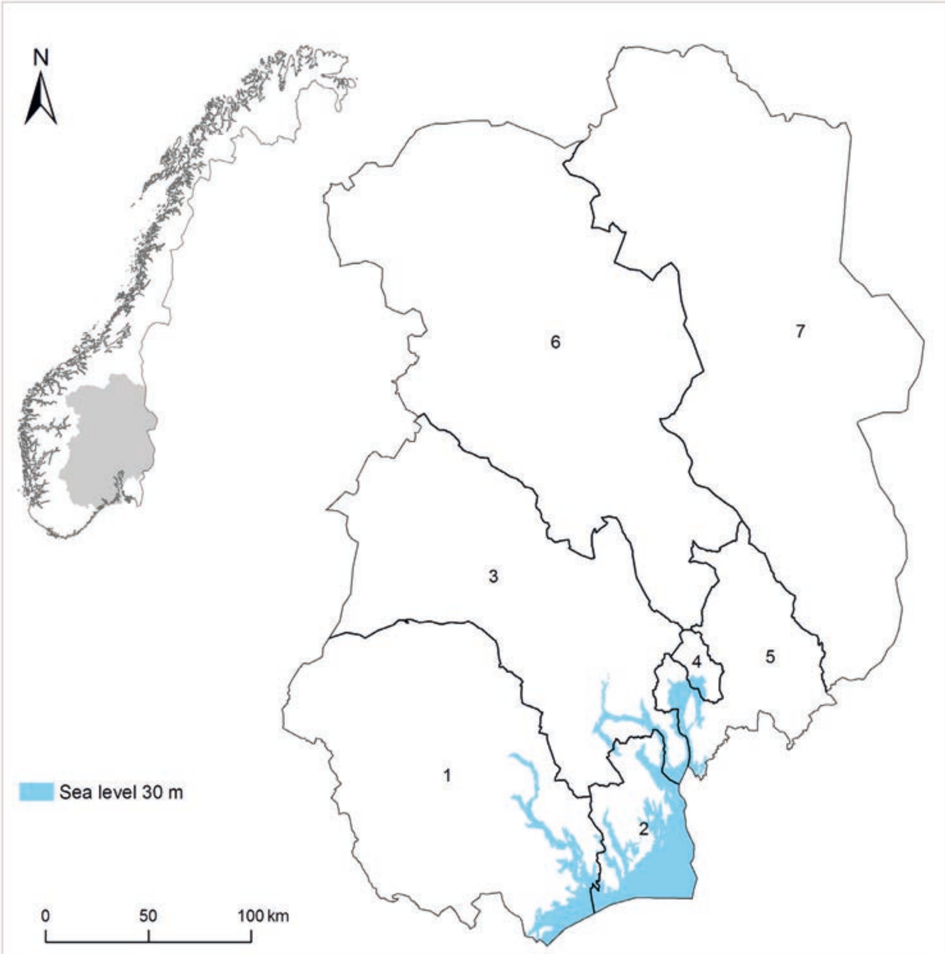

Figure 1. Seven counties in East Norway: 1. Telemark, 2. Vestfold, 3. Buskerud, 4. Oslo, 5. Akershus, 6. Oppland, 7. Hedmark.

based and developed in line with the CIDOC-CRM concept (Jordal, Uleberg & Hauge 2012: 256). The artefact catalogues, published and handwritten, have been digitised and converted to the MUSIT database. Original terminology for place names, artefacts, and raw materials have been kept as old classification events, and new, updated terms are consecutively added as new events.

The archaeological museum in Oslo, Universitetets Oldsaksamling, was founded as part of the University in 1829 and is now part of KHM. KHM is responsible for archaeological excavations in East Norway, and archaeological finds from this area are curated by this museum and registered in the MUSIT database (Matsumoto and Uleberg 2015b). The majority are georeferenced to a cadastral unit, but some have exact site coordinates. Given the long history of the collection, it is natural that some finds can only be georeferenced to wider areas like a parish or municipality. Metadata to describe the accuracy of the provenance are recorded in the database, and different sets of artefacts can be selected for analysis at different scales (Uleberg and Matsumoto 2015). The applied set of metadata is in accordance with the Norwegian standard for georeferenced information, SOSI (Kartverket 2016). The precision levels that are used in this paper are the equivalents of site and cadastral unit.

Representativity

The finds included in this analysis are georeferenced with an accuracy of cadastral unit or site. The question of representativity should address whether the visualisation includes a sufficient number of sites to capture the variation in tasks performed in the landscape during the Stone Age.

Generally in Norway, Stone Age finds have been abundant close to the coast and in the high mountains, but scarce in the intermediate woodlands and valleys. This pattern could be a result of modern activity rather than a reflection of Stone Age taskscapes. Single finds dominated the artefact assemblage from the seven counties presented here (Figure 1) as late as 1940, and many of them were accidentally found during farming. However, a study comparing the number of single finds with area of farmland in municipalities in Vestfold and southern Buskerud could not demonstrate a covariation between these two factors. This indicates that the distribution map is not only a reflection of modern farming. The number of surveyed and excavated sites increased from the late 1950s onwards as the development of hydroelectric power in the mountains led to the discovery of numerous sites near lakes and rivers (Glørstad 2002; Glørstad 2006; Indrelid 2006). From the 1980s there have been larger development projects producing new knowledge about the intermediary zone (Boaz 1998; Stene 2010), and in recent years the construction of modern infrastructure have provided more knowledge about Stone Age landscape use around the Oslo Fjord (Damlien and Solheim 2017; Glørstad 2004; Jaksland and Persson 2014; Melvold and Persson 2014; Reitan and Persson 2014; Solheim 2017; Solheim and Persson 2018).

The archaeological surveys included in the development plans related to hydroelectric power in Norway from the late 1950s marked a beginning of systematic archaeological surveying, and today all development plans involve documentation of cultural remains from all eras. The national systematic archaeological surveys from the 1960s were mainly concentrated on Iron Age sites, but also included Stone Age sites. This development is reflected in the Stone Age collection, as new accessions are more and more dominated by finds made more systematically by archaeologists. However, the surveyed areas are generally not chosen by archaeologists' research interests, but determined by developers' interests and concerns (Indrelid 2006: 21).

This selection of areas can be seen as detriment to the archaeological research, but construction work also sends archaeologists into areas that otherwise would not be studied. Surveys in the initial phase of road and railway planning are carried out within rather wide corridors, and from an archaeological point of view this can be seen as an arbitrary path through the landscape. However, the survey methodology will be influenced by the expectations and research interests of the archaeologists doing the survey. As an example, digging of test pits will be used more frequently in surveys concentrating on Stone Age sites than when the focal point is remains from the Iron Age or later (Prescott 1995: 38–43).

An example of this can be found in the surveys in the Oslo fjord area. The Ice Age ends around 12,000 BP, and the subsequent isostatic uplift has given the fortunate situation that height above sea level is related to archaeological periods. The earlier coastal sites are always at a higher altitude than the later. The shoreline at the end of the Ice Age is now at a height of 220 m a.s.l. in the inner Oslo fjord. The isostatic rebound was strongest shortly after the Ice Age when the shore displacement curve for Vestfold indicates a 30 m rebound within 400 years, which gives an annual average of as much as 7.5 cm (Jaksland 2014: 16–17). The changes during the Neolithic were more gradual. A sea level of around 30 m higher than the present can be used as an approximation for the situation around the Middle and Late Neolithic in the inner part of the Oslo fjord.

Recently, a site at 193 m a.s.l. in Akershus dated to 11,000 BP was excavated due to a new railway line in the area (Eymundsson and Mjærum 2015). Parts of the new highway through southern Vestfold were planned further away from the coast and at a higher altitude than the existing road, and the surveyed transect cut through previously unknown Early Mesolithic sites between 95 and 125 m a.s.l. In calendar years, this is equivalent to the period around 11,200 BP to around 10,800 BP (Jaksland 2014: 16–17). Further north in Vestfold, nine Middle Mesolithic sites were excavated where the highway corridor passed through landscapes between 49 and 70 m a.s.l. (Damlien 2013: 8–15). All these sites are interpreted as coastal sites that are now in forested areas. Corridors at lower altitudes have given more knowledge of Neolithic occupational sites. The Svinesund project (2000–2003) excavated sites in Østfold east of the Oslo fjord between 55 and 28 m a.s.l, equivalent to a shore line dating between 6300 BC (Late Mesolithic) and 2800 BC (Middle Neolithic).

Shorelines should, however, only be used as a *post quem* dating method. A site at 90–93 m a.s.l. in southern Vestfold was interpreted as a Mesolithic site during the survey, but diagnostic artefacts and C14 dates from the excavation revealed that it could be dated to Late Neolithic or Late Neolithic/Bronze Age and interpreted as a forest hunting camp (Jaksland

and Kræmer 2012: 226–227). The Svinesund project also excavated sites that were at a distance from the coast when they were inhabited. These sites corroborate that the Late Neolithic (2350–1700 BC) is a period with more sites further from the coast and generally in areas well suited for agriculture or pastoralism (Glørstad 2012).

All of these sites were found during surveying connected to modern development. It can be argued that the combined modern archaeological surveys and collected stray finds give a reasonably good representation of the distribution of prehistoric human activity in the landscape. The archaeological survey follows transects through the landscape determined by modern planning, and the strategy will be determined by expectations based on previous archaeological knowledge. It is, however, necessary to aggregate the archaeological material in ways that make it possible to visualise spatial analyses that can elucidate connections with different landscape types.

Landscape Categorisation

Spatial analysis of archaeological finds has been done in relation to a number of geological, geographical, and topographical variables. The purpose has often been predictive archaeology, and sites have been analysed in relation to variables like slope, soil types, and distance to water. This kind of analyses is sensitive to the scale of the geographic data, and in many cases it can only use finds that are georeferenced with high accuracy. A more holistic approach combines a set of distinct variables in the definition of landscape areas and this allows an inclusion of finds with lower accuracy. This approach can also reflect how the landscape is understood and created by people living and moving in it.

The Norwegian Institute of Land Inventory (NIJOS) developed a landscape reference system for Norway based on a method from the US Forestry Service and adapted in collaboration with the Institute of Landscape Architecture at the Norwegian Agricultural University (NLH). The landscape system is described at three different geographical scales: agricultural region, landscape region, and subregion. The three-dimensional content and the interaction between cultural and natural factors are important. This classification represents a multidisciplinary understanding and holistic evaluation of the landscapes. The description of the landscape character is based on six components: major landform, geological composition, water and waterways, vegetation patterns, agricultural areas, and buildings and technical installations. The final division into subregions was done in meetings with representatives from county departments for cultural heritage and agriculture and nature conservation. The outcome was a division into 45 landscape regions and 444 subregions. The borders of the subregions were defined from maps of the scale 1:250 000 (Puschmann 1998). Of the 444 subregions, 175 are within KHM's museum district. The map scale level is important to understand the accuracy of the borders, and to decide which accuracy levels in the archaeological material that can be analysed in reference to the subregions (Uleberg and Matsumoto 2016).

Landscape categorisations based on this system have earlier demonstrated that Puschmann's regions are quite useful for archaeological studies. Solheim (2012) has created broad categories based on Puschmann while Matsumoto and Uleberg (Matsumoto and Uleberg 2015a; Uleberg and Matsumoto 2015; Uleberg and Matsumoto 2016) have created different intermediate categories to find patterns in site distribution at different scale levels. This paper will use Puschmann's subregions to explore how the transition from Middle to Late Neolithic society is reflected in the archaeological sites in the landscape.

Experienced and Created Landscapes

The purpose of archaeological surveying is to register traces of human activities in a landscape. Each activity or sequence of activities can be described as events, an action taking place at a certain place and a certain time involving a single person or a group of people. The traces are grouped as sites, and in the case of Stone Age sites, the area is defined through a combination of topographic features and positive test pits.

Each event exists within a defined part of a spatiotemporal continuum. The archaeological notion of a site invites a delimiting aspect of an event. This is of course necessary when the event is registered as an entry in a database and a Geographical Information System (GIS). This reflects the general understanding of space, where we give names to cities, valleys, and a range of other defined parts of the continuous landscape around us to be able to refer to them. Anyhow, points on a map tend to direct our understanding towards limited, secluded spaces (Welinder 1988).

Probably the practical aspects of the site have kept it a widely used concept in spite of some aspects of it being criticised several times (e.g., Clarke 1972). One suggestion has been to replace the site by the concept of an archaeological landscape. Landscape archaeology employs spatial relationships of artefacts and features to understand how the landscape was used (Crumley and Marquardt 1990; Wagstaff 1987). The archaeological landscape can be defined as a surface within a certain timespan, an approach that can give a better understanding of the totality of human behaviour. An analysis without initially defined sites can give a more accurate definition of artefact clusters and can include off-site elements like cultural residues and paleoenvironmental data (Zvelebil, Green & Macklin 1992). Landscape archaeology could in this way achieve a more objectified description of human interaction with landscape. This effort to objectify the relationship between humans and landscape is also evident when the model is expressed in terms of organisms moving across a landscape (Stafford and Hajic 1992). This highly functional view of archaeological landscapes contrasts with the phenomenological view where all elements are endowed with meaning and deliberately placed in the landscape (Tilley 1994).

The landscape experience is different for people with different intentions. A study of pastoralists and fishermen in North Norway has shown how these two groups look for different traits and features and register different details in the landscape surrounding them (Meløe 1989). Pastoralists look for signs telling them when the grazing in the mountains can start, while fishermen look for signs indicating where the richest catches can be made. A good dwelling site for a pastoralist has good grazing conditions where the animals can be controlled and protected. A good dwelling site for a hunter/gatherer can be a place near animal trails. These different ways of understanding the landscape are then reflected in how the sites are placed in the landscape (Uleberg 2003; Uleberg and Matsumoto 2007).

Landscape archaeology has turned away from natural science to a view inspired by the humanities. The landscape is perceived, experienced, created, and transformed by people performing tasks. Tim Ingold set focus on this aspect of humans' relation to space by introducing the term taskscape (Ingold 1993). The concept of taskscape leads us to look for the active relation between humans and the time and space they live in; however, Ingold has later stated that he prefers the term landscape because of the connotations it has (Ingold 2017: 26).

A taskscape is created through the tasks performed by people in a space. Tasks are generally repetitive and can be described as cyclic, recurring events. Different tasks will have different duration, repetitiveness, and different spatial distribution. A task can result in objects that can be found during an archaeological survey, but not all tasks will leave tangible traces. An example of a task is the production of expedient stone tools. This is a task, an event, which is of short duration, can be recurring several times at the same place, and even be part of a larger event like a seasonal hunting of migrating reindeer. A place where a wide range of different tasks are performed can be identified as a habitation site, while a place with specialised tasks can be described as a butcher site, or simply a wood-procurement site. The term off-site can be used for a place where several independent but recurring tasks have been performed (Binford 1980). Places with recurring events have been described as persistent places (Schlanger 1992) but can better be seen as attractors; places where the artefacts are tangible evidence of the tasks performed there (Uleberg 2003; Uleberg and Matsumoto 2007).

Attractors in Nonlinear Systems

The taskscape is created by the combined trajectories of all tasks of short and long duration. These interwoven trajectories are an extremely complicated nonlinear system with minute variations that are irrational, accidental, historical, and specific (Spencer-Wood 2013: 5). This will probably be a better modelling of actual human behaviour than the equilibrium, slow change and rational behaviour that system theory otherwise presupposes. Nonlinear systems theory gives an opportunity to introduce sudden change without the influence of external factors. This is a property of the self-contained system that can shift between order and chaos without external influence.

Change can be triggered by small deviations inherent in the system and make it oscillate to chaos. The self-contained system can also go from chaos to a new equilibrium as a result of internal mechanisms (Luhmann 1992).

One way to approach an understanding of interaction and movement is by visualising the system through its attractor. The attractor is the state that the system converges to. A simple, two-dimensional system like a pendulum will eventually come to a stand-still as it has converged to its point-attractor. Nonlinear systems can converge towards much more complicated attractors which are called strange attractors. The strange attractor has a deterministic but totally aperiodical path. The movement converges towards the attractor, but two paths close to each other can diverge and follow different developments. The only way to describe such a system is by observing the trajectory of the strange attractor (McGlade 1995: 119–120).

In the case of past societies, it is not possible to describe the attractor which is how people moved through the landscape or produced artefacts. This attractor can, however, be visualised indirectly; by studying its Poincaré section, a hyperplane intersecting the strange attractor. The Poincaré section can be obtained from an m-dimensional attractor through the intersections of a continuous trajectory with a (m−1)-dimensional surface in the phase space. In our case, m is the 4D time–space continuum and the (m−1) surface is the 3D landscape with its sites and artefacts (Tsonis 1992: 83; Uleberg 2004: 445).

Another aspect of the Poincaré section that makes it applicable to archaeology is that it can be obtained by sampling the system occasionally, and not necessarily continuously (Tsonis 1992: 83). Not all activities will be registered in the archaeological record. The finds in the landscape will be the Poincaré section, and important variables will be landscape and find density that can incorporate a wide range of chronologically defined subsets. It follows that it is not necessary to know all sites in an area to give a valid description of the landscape use system. Such visualisations will feed the map-based Exploratory Data Analyses (EDA) (Andrienko and Andrienko 2006) that we will return to later – giving a new understanding leading to new interpretations followed by renewed clustering and new visualisations.

Turning back to the Stone Age in East Norway, it is rare to find sites with a stratigraphy that makes it possible to discern separate visits to the same site. Each site may have been visited several times with regular or erratic intervals. It is events taking place in the 4D time–space continuum and this material that can be analysed as a 3D-Poincaré set. The Poincaré set includes sites with multiple occupations or visits within a wide time span. It is scalable in the sense that it can be used to understand movements at a site or across regions. This view is possible because the focus is on accumulation at certain places through time and not detailed activities at special occasions (Uleberg 2004).

Map-Based Exploratory Data Analyses

Map-based Exploratory Data Analyses (Andrienko and Andrienko 2006) is an iterative process where results and new insights create new input (Figure 2). Different segments of space and time are defined in a process of aggregation and segmentation where the definition of boundaries is given special attention. This can be referred to as combinations of the Modifiable Areal Unit Problem (MAUP) (Harris 2006) and the Modifiable Temporal Unit Problem (MTUP) (Cheng and Adepeju 2014). The discussion of MAUP addresses the fact that the geographical data are correct at the scale they were prepared for and should not be used at a very different scale. This is actualised as digital data can be studied and combined at any scale in a GIS. The landscape subregions used in this study are constructed for a map scale of 1:250,000, and this must be kept in mind when combining these data with other datasets. They form a continuous space within the outer borders of the study area. Similarly, MTUP addresses the problems of separating different time intervals. Here, the temporal scale levels have been set as broad archaeological time periods, and MTUP must be considered to avoid a misleading combination of wide and narrow timespans. Certain patterns and covariances will be visible only at certain scales, and this will determine the questions that can be posed. The analysis can be too detailed for a pattern to be recognized or too large so that more detailed and important associations are lost. The scale of explanation must relate to

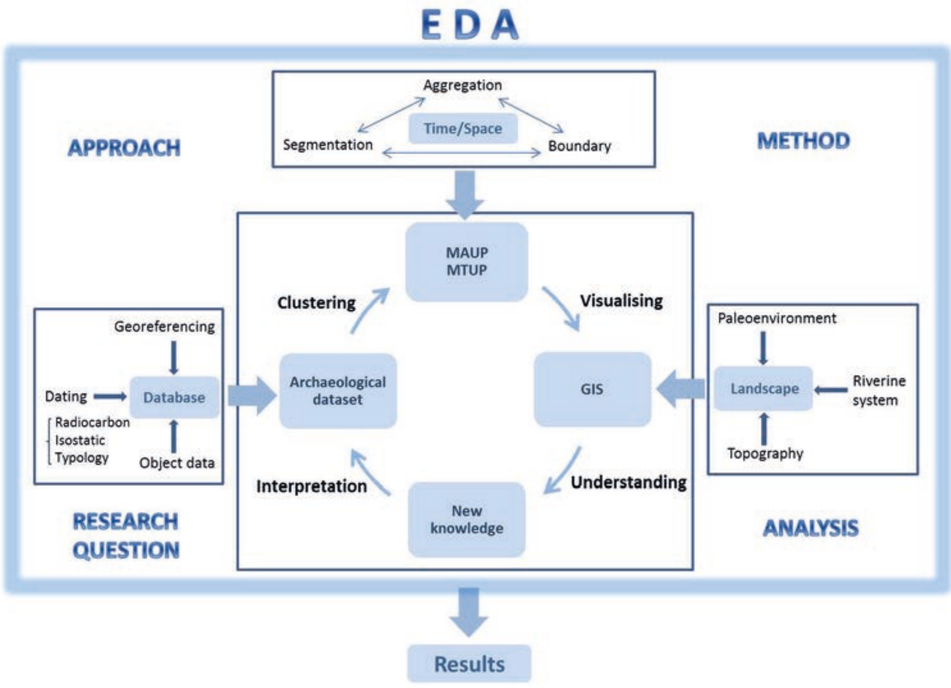

Figure 2. Exploratory Data Analyses (EDA) using the MUSIT database and landscape analyses.

the scale of observation (Harris 2006; Holdaway and Wandsnider 2006; Uleberg and Matsumoto 2015).

The map-based Exploratory Data Analysis starts with the general knowledge that is necessary to interpret the archaeological dataset. The dataset is taken from the database with object information, dating ,and georeferences. The research question guides the clustering in lieu of the MAUP and MTUP. They are both a consideration of segmentation, aggregation, and boundaries of the chosen time/space. The subsequent GIS visualising can include the landscape with elements like topography, riverine systems, and paleoenvironment. This leads to new understanding and new knowledge that starts a new cycle (Figure 2).

In this process, the archaeological dataset is clustered according to the spatiotemporal divisions and visualised with a GIS. It is important that the temporal and spatial scale levels in the analysis correspond with the accuracy of the basic data (Holdaway and Wandsnider 2006). Each archaeological site can be the result of one or several events, each of longer or shorter duration. The archaeological material could be from a series of consecutive or separate events spread out over a longer time span. A site that is the result of many such events cannot be dated precisely. The distribution along the time axis can no longer be seen. The original 4D time–space attractor is projected on the landscape and can only be documented as a distribution map, a 3D-Poincaré set. Diagnostic artefacts at the site could be given a more precise date, but expedient tools and debris can only be traces of events that took place sometime during the period.

The Middle Neolithic–Late Neolithic Transition

The transition from the Middle to the Late Neolithic in Norway is seen as a period of marked and lasting changes in economy, technology, and social organisation. There were several local groups during the Middle Neolithic, and marine activity was an important part of the subsistence economy. Agriculture and pastoralism become more important at the onset of the Late Neolithic, ca 4300 BP, and sites can be found at further distances from the coast. There are even indications of metal prospection (Glørstad 2012; Melheim 2012; Prescott 2009; Prescott 2012; Østmo 2012).

The Scandinavian flint daggers are impressive objects made with the pressure-flaking lithic technology which is a diagnostic treat in the Late Neolithic/

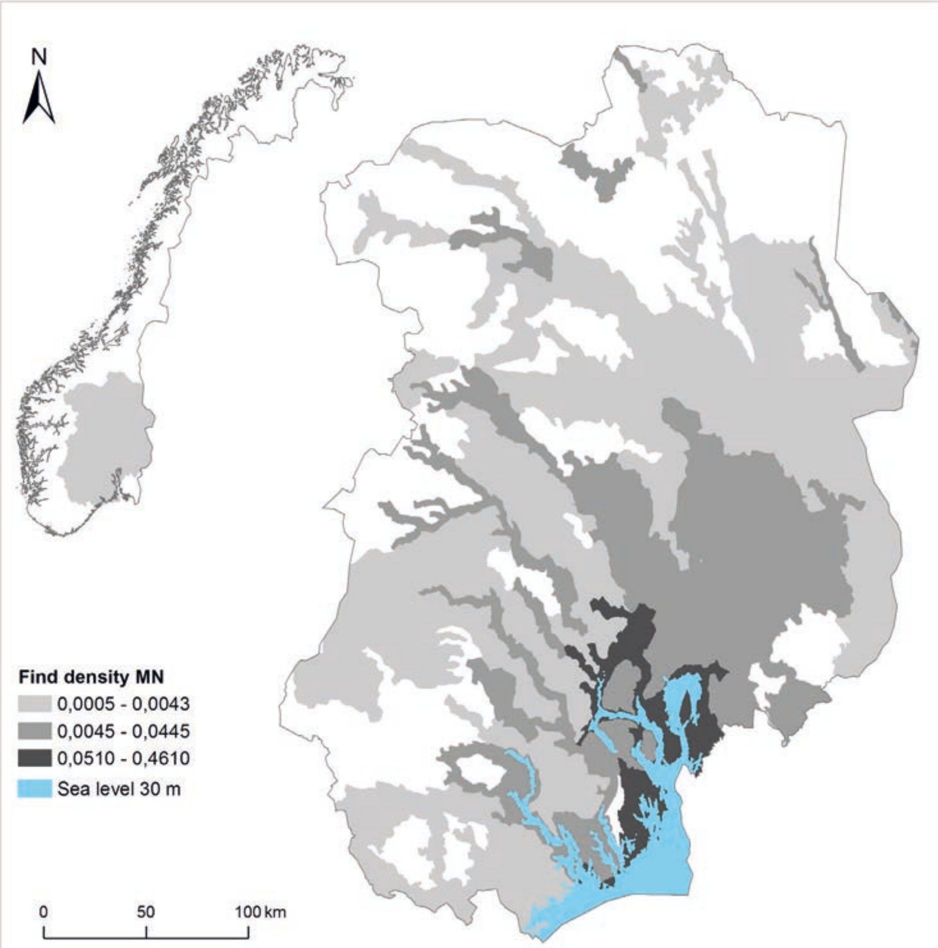

Figure 3. Middle Neolithic (MN) find density in landscape subregions.

Early Bronze Age. Flint daggers were imported to Norway, in some cases as almond-shaped roughouts (mandelflint). Most of the flint daggers are single occurrences, but they can occasionally be found in graves, as evidenced in the few monumental stone cists that occur in Norway (Østmo 2011). The flint daggers belong to a society with a warrior class and reflect the contact with the Bell Beaker Culture (Glørstad 2012; Prescott 2012; Østmo 2012). Flint daggers are categorised in six main types (Lomborg 1973), that have a chronological as well as geographical distribution (Apel 2001; Madsen 1978). The production of the earliest type of flint daggers, Type I, can be located to Jutland in the western part of Denmark. The later types were produced on the isles in Eastern Denmark and in the adjoining part of Sweden (Apel 2001). The early daggers from Jutland shows increased contact across Skagerak and also reached the Oslo fjord further north (Østmo 2012).

The fact that flint daggers have been found as grave goods in stone cists indicates the special status of these artefacts in the Late Neolithic society. Although most of them are single finds without a reliable context, it is reasonable to assume that they were deposited at meaningful places in the landscape, places that had been chosen for a grave or an offering. The daggers also signal that the surrounding landscape was controlled by people with power and status as well as contacts that enabled them to own such a precious object (Apel 2001; Østmo 2011: 166–167).

The daggers of type I and II made in the first 400 years of the Late Neolithic have parallels in bronze daggers in Western Europe and the British Isles. The daggers of type III, IV and V were made during the last 250 years of the period and have parallels in the Unetice culture in Middle Europe, especially in Moravia and Bohemia. The production of Scandinavian flint daggers decreased markedly towards the end the period, but the dagger of Lomborg's type VI

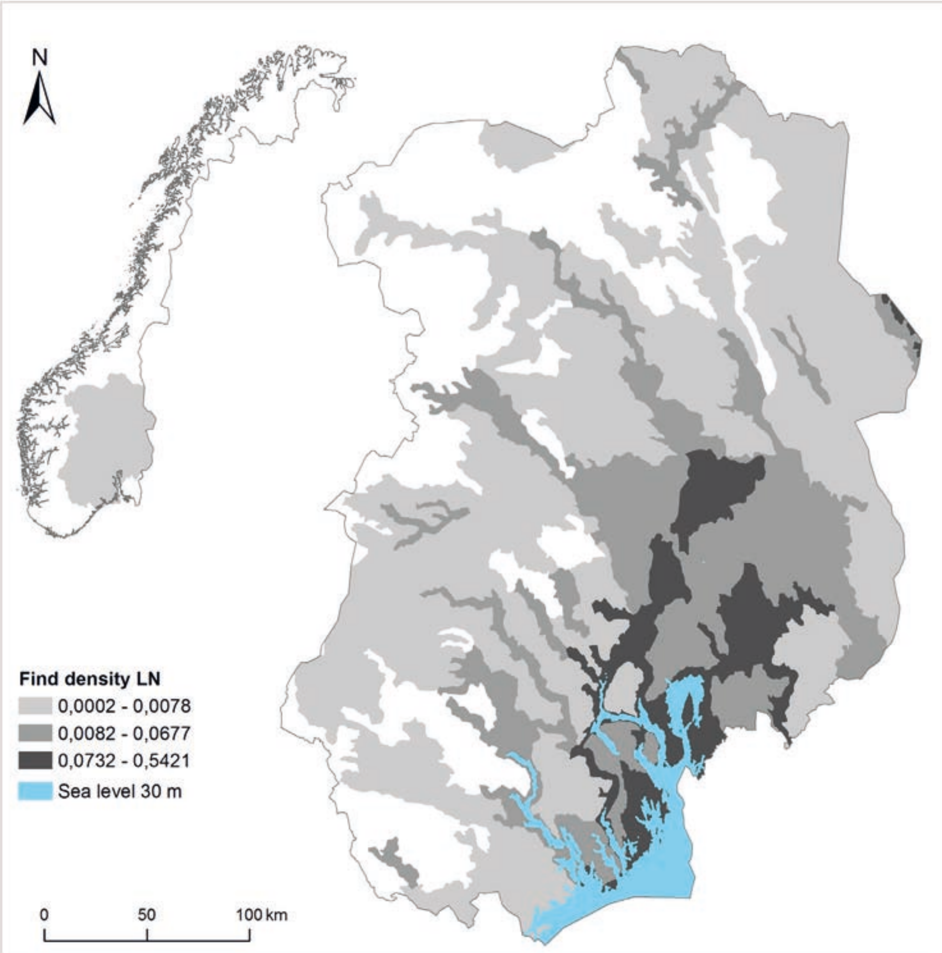

Figure 4. Late Neolithic (LN) find density in landscape subregions.

continued into the early part of the Bronze Age (Apel 2001: 259–275; Madsen 1978). The flint daggers can safely be presumed to be signs of cultural contacts between Norway and the rest of Europe during the Late Neolithic.

The influence from the Bell Beaker Culture is also evident in the two metal objects in this study area. They are flanged axes that can be dated to Late Neolithic I (4300–3900 BP). One (C25254)[1] was found in a river close to the Oslo fjord in a high-density subregion, the other (C7978) at the innermost part of a narrow fjord adjacent to a high concentration subregion. This appearance already in the first part of the period could indicate that metal had a wider role than just being exotic items of high value. Such finds in more peripheral areas may even be seen in a metal prospection context (Melheim 2012).

1 Individual objects or sets of objects are numbered with the prefix 'C' in KHM's catalogue.

Methods and Results: The Visualised Distribution

The general dating of the sites in the MUSIT database refers to archaeological periods. The dating can be based on typology, technology, C14-dating, or shore line curves. In addition, a more specific or even different archaeological period can be indicated by single artefacts from a site. The finds include artefacts from sites dated to the Middle or Late Neolithic as well as single artefacts typologically dated to these periods. Puschmann's landscape subregions are chosen as the spatial scale level. The corresponding accuracy level for the georeferenced finds is site or cadastral unit. With these limitations, 837 Middle Neolithic and 1812 Late Neolithic artefacts are used in the current analysis.

The maps show the archaeological finds divided in three classes. The values that create the classes are calculated by dividing the number of points in

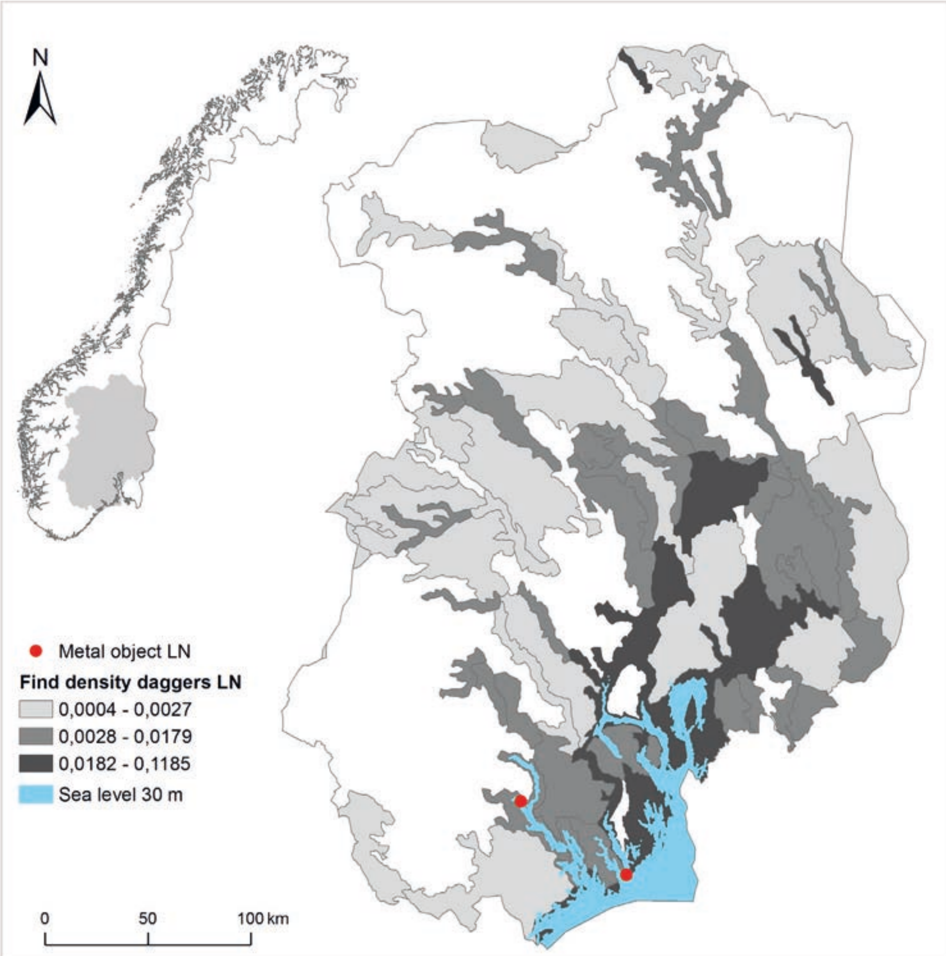

Figure 5. Late Neolithic (LN) metal objects and flint dagger find density in landscape subregions.

the Poincaré set by total area in each subregion with a sea level 30 m higher than the present. The total area includes lakes and rivers. The class breaks are calculated as geometric intervals. The geometric intervals are defined by an ArcGIS algorithm designed for continuous data. It creates geometric intervals by minimising the square sum of element per class. The geometric coefficient for the classes in this dataset is 10.

The map (Figure 3) shows that subregions with the highest concentration of Middle Neolithic finds are concentrated to the narrow areas around the Oslo fjord. In addition, there are areas with intermediate find concentrations along the larger river systems, especially to the north.

The map of Late Neolithic finds (Figure 4) presents a continuity in the concentration around the Oslo fjord.

Our preceding studies of axes, sickles, and daggers have indicated that the development from the Middle to the Late Neolithic is an intensification and expansion into the interior areas (Uleberg and Matsumoto 2016). A comparison of Figures 3 and 4 indicates a higher concentration of activity in the landscapes best suited for agriculture. The interior areas with intermediate concentration shift from one period to the next. The interior areas northwards from the coast are along the river systems, and it should be noticed that the inland areas with highest Late Neolithic concentrations are on clayish or Silurian soils which are especially well suited for pastoralism. There are a few areas with higher concentrations far from the fjord that can be related to metal prospecting.

Flint daggers and metal objects are prestige objects that indicate a stratified society. The two metal objects are found at the Oslo fjord, but not in the area with the highest concentration of finds. The distribution of flint daggers as densities and the two Late Neolithic metal objects as points (Figure 5) have the same high-density areas as the overall Late Neolithic finds, but fewer intermediate areas. This indicates that groups in the best agricultural areas had contacts that gave them access to such prestige objects. This visualisation of the find distribution supports the claim that the activity in the Late Neolithic was more concentrated on agricultural activity (Glørstad 2012).

Landscapes Created Through Events

The analysis of the existing dataset has enhanced aspects of the transition from Middle to Late Neolithic in East Norway; the interior areas become more inhabited, and landscapes with better conditions for agriculture, also at a distance from the coast, have a higher frequency of more prestige artefacts.

This visualisation is based on the idea that all artefacts can be seen as points on a Poincaré map that describes the underlying nonlinear system. In this way, all artefacts which meet the criteria for dating and provenance precision are included in the analyses. It makes it possible to include both excavated material and finds with less precise provenance. The artefacts have been aggregated according to predefined landscape areas, and the difference between the Middle Neolithic and Late Neolithic can be seen as a movement into the interior areas that favours the landscapes best suited for agriculture.

This paper has analysed wide time categories, as the Middle and Late Neolithic have been treated as units. Future work could look at finer chronological divisions and also include more paleoenvironmental information. The Norwegian Late Neolithic is a period with increasing cultural contact with other parts of Europe. The most distinctive artefacts, the flint daggers, are imported as finished products or next step could be to analyse the spatial distribution of these artefacts at more fine-grained temporal scales and understand more of the landscapes created through these actions.

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In the Land of a Thousand Cities: Evaluating Patterns of Land Use in Bactria through Survey and Remote Sensing

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Abstract

Bactria, a region today comprised of parts of Afghanistan, Turkmenistan, Uzbekistan, and Tajikistan, has historically been the homeland for a wide range of cultural groups that have produced a palimpsest of archaeological sites. Focusing on those parts of Bactria within the northern provinces of Afghanistan, this paper draws on decades worth of archaeological survey and excavation to investigate the history of land use in this region and its relationship to the highly variable landscape. Periods of increase and decline in site frequency are identified which, through analysis of topographic, environmental, and ecological data derived from remote sensing, are examined in respect to where increases are occurring and how that may reflect land-use and subsistence strategies of different groups. By doing so, a better understanding of how these different groups historically utilized the landscape is achieved, while also emphasizing the significant changes that occurred during transitions between different historical periods.

Keywords: Bactria, settlement pattern, land use, GLCC, spatial statistics

Introduction

Known since antiquity as the *land of a thousand cities*, a trope frequently employed by Mediterranean geographers and historians,[1] Bactria was a region that, at times, experienced periods of rampant urban development, wealth, and agricultural prosperity (Figure 1). However, this rather frequently contested region was also met with long stretches of unrest, destabilization, and settlement dispersal: an oscillating trend that can still be witnessed within some parts of the region today. This paper seeks to explore these periods of growth and contraction through the synthesis of archaeological, topographic, and environmental data. We outline the spatial characteristics of human occupation of the region on a diachronic scale, examining not only when there are expansions in the number of sites, but where. In so doing, we address the characteristics of land use and occupation during distinct chronological periods while also shedding light on long-term trends and patterns that continue despite abrupt changes in political or cultural organization.

At a general level, we predict that increases in the number of sites occur primarily in areas suitable for irrigated agriculture, and that it is primarily during such periods of growth that increases also occur in more marginal areas. Conversely, we predict that decreases in site counts result in the abandonment of these marginal areas and a contraction of occupation to rain-fed or irrigated agricultural areas. We also predict that increases in site counts will correspond to a higher density of sites with clustering positively correlating with site frequency at local scales. This

1 Apollodorus of Artemita (fr. 6.9), in his fragmentary history of the Parthian Empire, describes the region as εὐκρατίδαν γοῦν πόλεις χιλίας, an account redeployed by Strabo 15.686, who employs the same phrase. Likewise, Justin 41.1.8 refers to the region as *opulentissimum illud mille urbium* Bactrianum imperium in his broader geographical treatise on the region.

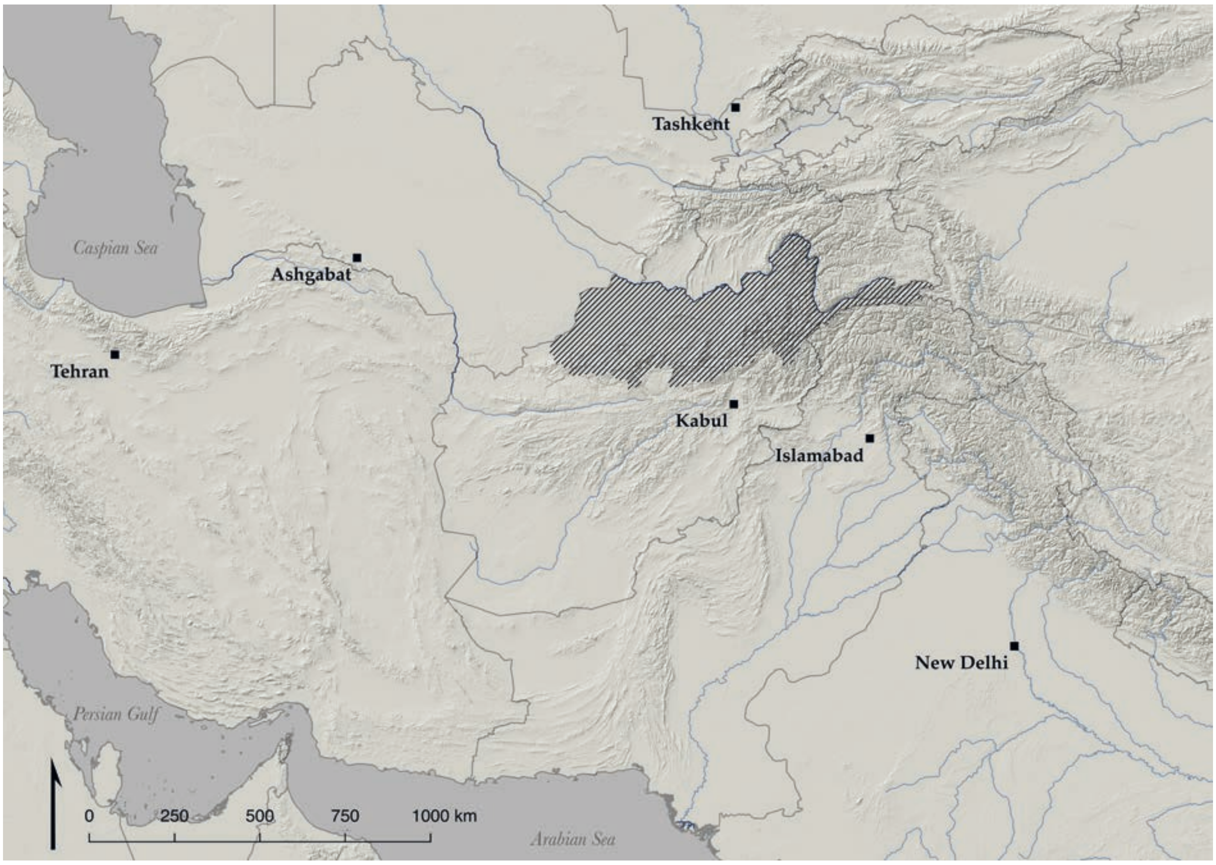

Figure 1. Map showing Bactria (hatched area) and neighboring modern countries.

would indicate the preferential occupation of areas with preexisting settlement. These predictions are largely based on the assumption that marginal areas, which we define as grassland and shrubland, will only be occupied if sufficient population pressure prevents exploitation of more productive areas, such as dryland and irrigated cropland – as behavioral models like the Ideal Free Distribution (IFD) predict (Fretwell and Lucas 1969; Winterhalder et al. 2010). We predict that variations from this model may be the result of conflict (i.e. preference for higher elevations for defensive reasons), an emphasis on particular subsistence strategies that exploit certain ecological zones (i.e. upland pastoralism), or a more variable land-use strategy in the region that other studies from north of the Amu Darya River have already noted (Stride 2007).

Regional Historical Overview

The region of Bactria consists of a topographically varied landscape, bordered rather dramatically by the Hindu Kush mountain range on its southern and eastern edges, the Karakum desert and grass steppes of Margiana to the west, and the Pamir mountains of Sogdiana that lead to the Central Asian steppes to the north (Holt 1999: 10; Rawlinson 1912: 1-2). The Amu Darya River, known in antiquity as the Oxus, runs through the center of the region, from the east to the west, eventually turning to the northwest to empty in the now-shrunken Aral Sea. This seemingly divergent combination of hot and cold, wet and dry, high and lowlands was a theme that was continually evoked in ancient geographic treatises, serving to mark Bactria as something of a land of opposites. The first century CE Roman historian of Alexander the Great, Quintus Curtius Rufus (7.4.26), summarizes this concept, remarking on the variable topographic and ecological nature of the region.[2]

The earliest archaeological evidence for urbanism in the region is associated with the Bronze Age civilization termed the Bactria–Margiana Archaeological Complex (BMAC). Comprising a series of major urban centers spread throughout the regions

2 The full passage reads as follows: "Bactrianae terrae multiplex et varia natura est."

of Margiana and Bactria—from the arid Karakum Desert in southern Turkmenistan, through the fertile valleys on either side of the Amu Darya, to the harsh terrain of the Hindu Kush — BMAC culture thrived from the late third to the early second millennia BCE. These early urban centers are characterized by a planned urban form, large-scale mudbrick architecture, major fortifications, and intensive irrigation (Askarov and Sirinov 1994). This irrigation, drawing from the large Amu Darya, as well as the smaller rivers that flow into it from the plateaus to the north and south, served to create broad fertile oases within an otherwise oppressive landscape, and allowed for the development of intensive agriculture on a large scale, alongside the continued practice of extensive pastoralism.[3]

Despite this longstanding tradition of urbanism in the region, the first definitive historical attestation of Bactria does not occur until the Achaemenid period, in the middle of the first millennium BCE.[4] Bactria was brought under Achaemenid control by Cyrus the Great in the 6th century, and first mentioned by Darius I as a Satrapy of the Persian Empire in the Behistoun Inscription of 520 BCE.[5] This inscription stands as the first marker of direct external control of Bactria, a trajectory that saw foreign interventions in the region by Hellenistic Greeks, Indo-Iranian Yuezhi states, Sasanian Persians, Turks, Mongols, Huns, and several Islamic Persian empires, all of which mixed with the already multicultural indigenous population. These administrative interventions, coupled with continuous trade with the Mediterranean, as well as South and East Asia, served to mark Bactria as a multicultural, cosmopolitan space. Each new era of cultural control brought novel perspectives toward urbanism and settlement patterning—often adopting characteristics from multiple cultural groups simultaneously—a feature that is preserved within the broad archaeological record of the region.[6]

Methodology

We hypothesize that periods of overall increased site frequency correspond to higher site density at relatively local scales and a preference for low-elevation and topographically flat irrigated areas ideal for intensive irrigation, that is paired with the exploitation of more marginal areas necessary to support increased populations, such as upland pastures. Conversely, we predict that periods of overall low site frequency correspond to lower site density and a less variable land use pattern that exploits primarily low-elevation areas suitable for irrigation. The combination of site density and land use classification is meant to evaluate both first and second order effects on the data.

First order effects are those that describe the average intensity of point patterns over a given area and are usually influenced by external variables, such as those employed here. Second order effects are those that influence the location of data points across a study area due to the location of neighboring points, due to some forces of attraction or repulsion inherent to the points themselves (Bevan and Wilson 2013: 2416).

Archaeological site data for this project was compiled from Ball and Gardin's (1982) *Archaeological Gazetteer of Afghanistan*, which synthesizes several decades worth of archaeological survey, excavation, and exploration within Afghanistan. Though the *Délégation archéologique française en Afghanistan* (DAFA) is planning an updated edition of this by now quite dated volume, the period of conflict and instability that followed its publication makes it a valuable record of sites that have since been damaged or destroyed, while also remaining more or less cur-

3 Evidence for this combined practice is found at Gonur Tepe, one of the most significant and well-studied BMAC urban sites. At this site, Moore et al. (1994) have conducted a thorough review of the intensive agriculture, large-scale irrigation, and herding practices that worked in tandem to support the large Bronze Age population at the site.

4 Potential earlier attestations of both the region and the name of Bactria are found in the Avestan Vidēvdād, where it is called Bāx'iš or Bāxδriš (Humbach 1966: 52).

5 The Behistoun Inscription (ln. 6) describes Bactria (Bâxtriš) as one of the 23 kingdoms under the control of Darius the Great. It also recounts a tale of a revolt in Margiana (Marguš), one of the minor satrapies within Bactria, led by Frâda, which was quashed by Dâdarši, the satrap of Bactria proper in 521 BCE (ll. 38-39).

6 See, for instance, the characteristics of Aï Khanoum, which features several distinctly Greek urban features such as large ashlar fortifications, a theater, and a series of Hellenic temples, while actively engaging with local architectural and artistic traditions, a practice witnessed in the form taken by local sculpture, and the presence of Persian and Mesopotamian architectural forms (Bernard 1987; Leriche 1986).

Period	Abbre-viation	Duration
Paleolithic	PL	50,000-8,000 BCE
Neolithic	NL	8,000-4,000 BCE
Bronze Age	BA	4,000-1,500 BCE
Iron Age	IA	1,500-530 BCE
Achaemenid	A	530-330 BCE
Seleucid	SE	330-250 BCE
Greco-Bactrian 1	G1	250-180 BCE
Greco-Bactrian 2	G2	180 BCE-1 CE
Kushan 1	K1	1-100 CE
Kushan 2	K2	100-200 CE
Early Sasanian	ES	200-300 CE
Kushano-Sasanian	KS	300-400 CE
Hephthalite	H	400-550 CE
Late Sasanian	LS	550-650 CE
Turkish Khanate 1	T1	650-800 CE
Turkish Khanate 2	T2	800-875 CE
Samanid	SA	875-1000 CE
Ghaznavid	GZ	1000-1050 CE
Seljuk	SL	1050-1150 CE
Ghurid	GH	1150-1225 CE
Chaghatai Khanate	C	1225-1380 CE
Timurid	TM	1380-1500 CE

Table 1. Chronological periods used in this study (adapted from Ball and Gardin 1982).

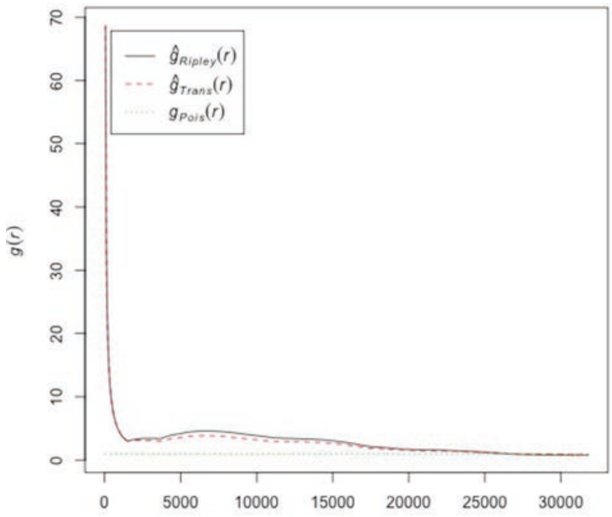

Figure 2. Plot of pair correlation function for sites during Paleolithic (PL) period. Distance (r) is in metres. gPois represents theoretical distribution of points under the assumption of CSR. gRipley and gTrans are empirical observations of the data. The farther above the gPois line, the more clustered the data.

rent. Even so, the synthesis of archaeological investigations by different projects over several decades, of varying intensity and analytical focus, necessarily makes a broad scale regional analysis of all these data problematic. Recording standards are inconsistent, with some projects recording a group of mounds as a single site while others recording such groupings as a series of individual sites. Overrepresentation of sites from certain periods may also be the result of differences in the diagnosticity of materials or the lack of specialists familiar with certain types of material, a problem common to all archaeological surveys (Millet 2000 53-59). For the identification of general trends and deviations, however, the wide temporal and spatial scope of the analysis should allow for the integration of these data despite their inconsistencies in recording or analysis.

With our survey area constrained within the boundaries of Afghanistan (a region of roughly 160,000 square kilometres), we selected sites from all provinces that bordered the Amu Darya River in the north. Working from the distribution maps provided in the Gazetteer, we then digitized the data provided for these sites. Attributes included coordinates provided in degrees minutes and chronological attestations, with sites lacking either of these attributes excluded from our dataset. While many site entries go into detail about possible functions of the site (e.g., urban settlement, fort, cemetery), we largely ignored these descriptions given their inconsistency and the unclear methods by which these characterizations were made. The sites used in this study thus represent cultural activity in general, rather than a focus on settlements of a particular function or nature. In total, 289 sites were mapped, covering a timespan from the Paleolithic to the Timurid period. This timespan follows the chronological divisions set by Ball and Gardin (1982: 372), which we adapted and divided into twenty-two periods (Table 1).

To test the above predictions about the relationship between site counts and density, we calculated nearest neighbor distances and the pair correlation. These statistics measure how site density changed between chronological periods while also measuring the scale at which these changes occurred. We recognize that chronological periods are not equal in length, and our analysis should be understood as

Code	Description	Characteristics
100	Urban and Built-Up Land	Majority of land covered by structures
211	Dryland Cropland and Pasture	Land alternates between periods of bare soil and vegetation, following rainfall trends
212	Irrigated Cropland and Pasture	Land alternates between periods of bare soil and vegetation, independent of rainfall trends
280	Cropland/Grassland Mosaic	Land covered by combination of cropland and grassland, with neither covering more than 60%
290	Cropland/Woodland Mosaic	Land covered by combination of cropland and woodland (vegetation exceeds 5 m in height), with neither covering more than 60%
311	Grassland	Land with herbaceous cover. Tree and shrub cover less than 10% of land
321	Shrubland	Woody vegetation less than 2 m tall and covering between 10-60% of land
330	Mixed Shrubland/Grassland	Land covered by combination of shrubland and grassland, with neither covering more than 60%
500	Water Bodies	Oceans, seas, lakes, rivers
770	Barren or Sparsely Vegetated	Most of land is exposed soil, sand, rocks, or snow with less than 10% vegetation

Table 2. USGS Land Use/Land Cover (Modified Level 2) classifications.

tracking changes between periods rather than over continuous time. The pair correlation function describes how density varies as a function of distance from each point (Baddeley, Rubak & Turner 2015: 225-230; Bevan et al. 2013; Stoyan and Stoyan 1994). It does so by creating rings around each point at certain distance intervals, within which points are counted. The statistic it provides is the probability of observing a pair of points separated by a distance (r) divided by the probability expected from a Poisson point distribution defined by complete spatial randomness (CSR). The empirical point pattern can then be evaluated as clustered or dispersed through comparison to this theoretical, null point pattern (Figure 2).

The distance at which point patterns deviate from CSR can also be assessed from this statistic, and in this study is used as a measure of the minimum distance at which the point pattern deviates most from CSR as calculated by the pair correlation function. A small minimum r value indicates clustering at a relatively small scale while a greater minimum r indicates clustering at larger scales – suggesting a more extensive pattern of clustered sites. For a more general measurement of distance between sites during each period, nearest neighbor distance was also calculated by averaging the distance from each site to its five nearest neighbors, per period, and then taking an average of all those values. The resulting value represents the average nearest neighbor distance of sites during each period, to the fifth neighbor. Evaluating these distances in conjunction with the information provided by the pair correlation function provides insights into the second order properties of site patterns in the region during each period and how they changed through time. These calculations were done in R using the *spatsat* package (Baddeley and Turner 2005).

Archaeological data were complemented by environmental and topographic data meant to evaluate the first order relationships between sites and these various factors over time. Topographic data were derived from 30-metre resolution digital elevation models provided by the Shuttle Radar Topography Mission (SRTM). Mean annual precipitation was provided by WorldClim Version2 (Fick and Hijmans 2017). Together, these two datasets generally relate to the suitability of the environment for various agricultural strategies and provide a coarse perspective on the variation within the study area that may detect macro-level trends in site location in respect to these variables.

For a more nuanced and higher-resolution perspective, land-use classification data provided by the Global Land Cover Characterization (GLCC) were employed (Anderson et al. 1976; Loveland et al. 2000). This dataset is based on unsupervised classification of 1-kilometre resolution Advanced

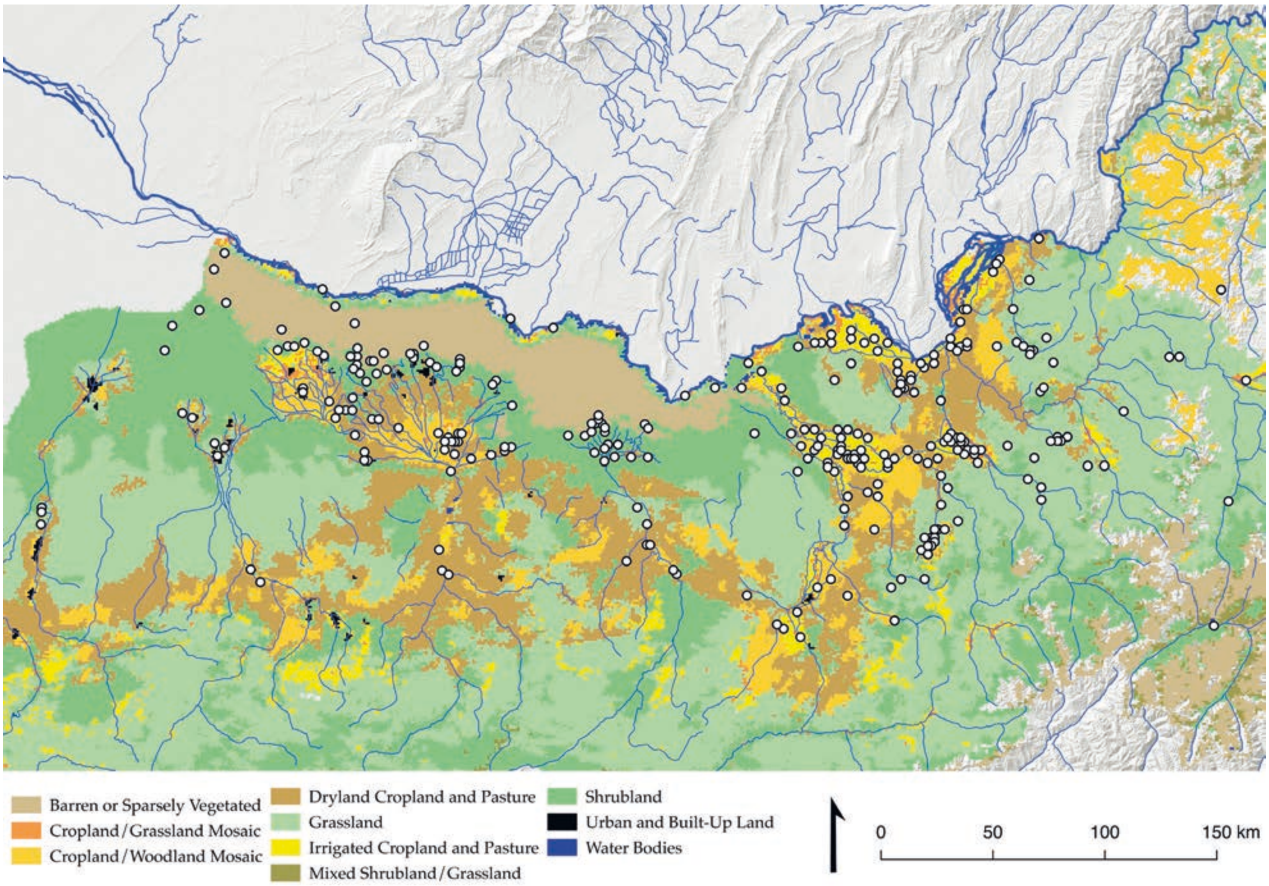

Figure 3. Land Use/Land Cover classifications with archaeological sites.

Very High Resolution Radiometer (AVHRR) 10-day Normalized Difference Vegetation Index (NDVI) composites, and provided by the Land Processes Distributed Active Archive Center (LP DAAC) and the United States Geological Survey (USGS). Of the twenty-four land-use types classified in the USGS Land Use/Land Cover System, ten had sites located within them (Table 2). The remainder were either land cover classes not found in this region (e.g. wooded tundra), or those that did not contain sites (e.g. herbaceous wetland). Long-term and high-resolution environmental data is required to determine whether significant environmental changes have occurred within this region during the temporal scope of this study that would alter the land-use classification of certain areas during periods of occupation. In lieu of such data, we assume that environmental conditions today generally reflect conditions during the majority of periods studied here, with areas suitable for irrigation today being those that could have been successfully irrigated in the past as well. On the other hand, the classification of some sites as within Urban and Built-Up Land or Water Bodies is due to the 1-km resolution modern imagery from which land-use types are derived, as well as the resolution of the spatial coordinates provided for the archaeological sites. Rather than reclassify these points into other classes, their classifications were maintained so as to remain consistent, and these sites and their land-use type were excluded from further analysis. Only one site was classified within mixed shrubland/grassland areas, during the K1-ES periods, and thus was also excluded from further analysis. Analyses of these data were conducted in R using the raster package (Hijmans 2016).

Bringing these data together, elevation, precipitation, and land-use information were extracted for each site, while spatial statistics and counts of sites were calculated for each period (Figure 3). From these data, we identify periods of relative site count increases and decreases, which are then explored further through analysis of environmental and topographic variables. In other words, we seek to identify when increases in site number and density within this region of northern Afghanistan occur, and in what ecological zones these increases occur.

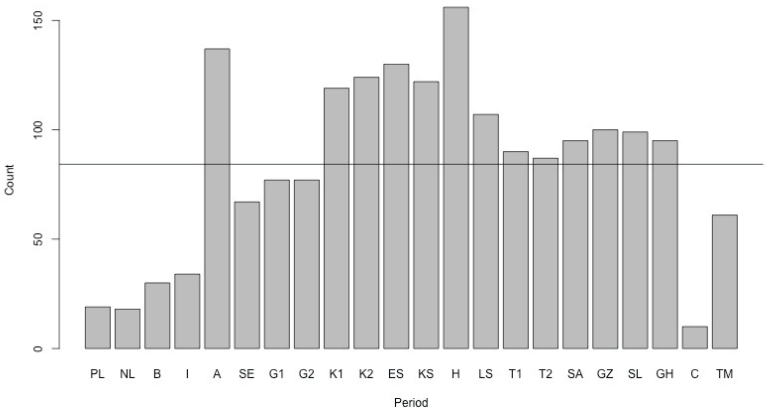

Figure 4. Number of sites per period, with average site count (84) shown by horizontal black line. For period abbreviations, see Table 1 and text.

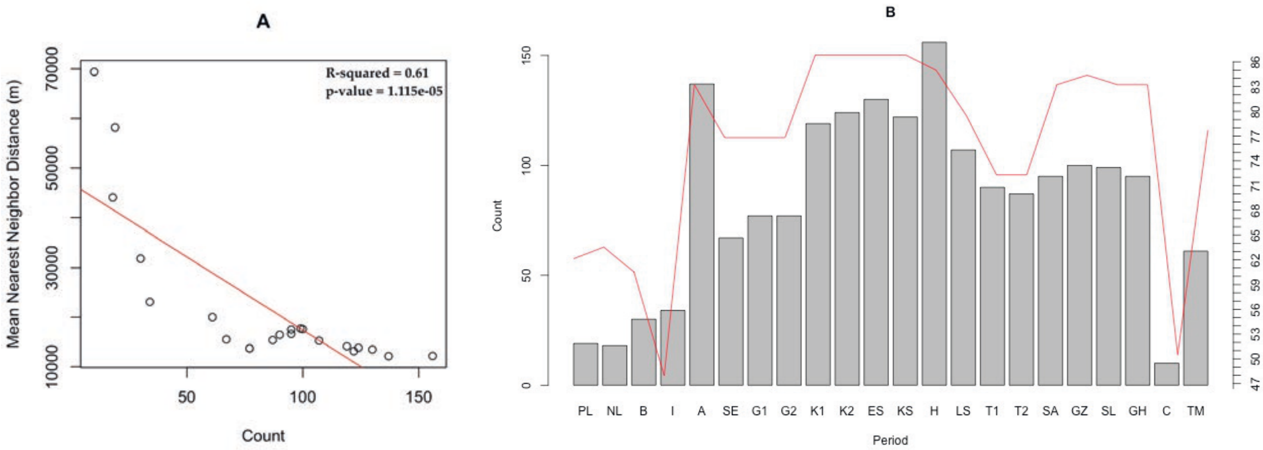

Figure 5. (a) Site distance plotted against site count per period and (b) minimum pair correlation function plotted against site counts per period.

Results

A simple breakdown of site counts per period reveals notable peaks in overall regional occupation (Figure 4). The Achaemenid period (A) is particularly pronounced and reflects the investment in the region attested in historical sources from the period (Leriche and Grenet 1988). This peak is notable both for the marked increase in site counts compared to preceding periods as well as the sharp fall during the Hellenic periods (SE-G2) that followed. Indeed, site counts in this region during the Bronze and Iron Ages (B-I) appears generally consistent, with a slight increase in count during the early first millennium BCE. The arrival of the Achaemenid Persians clearly had a massive impact on the region, with sites increasing by almost four times. After the conquest of Alexander, site counts decreased by half, with only a slight increase during the Seleucid and Greco-Bactrian periods. Yet even with this significant decrease, sites during the Hellenic periods were still about twice the number of sites before the Achaemenid period.

The Kushan and Sasanian periods (K1-KS) show another marked increase in site counts that, while fluctuating slightly over several centuries, comes close to matching the counts reached during the Achaemenid period. The gradual increases seen during the K1-ES periods, similar in magnitude to the increase seen during the SE-G2 periods, suggests stability and gradual growth, with the dip during the KS period historically attributed to conflict (Grenet 2006). Sharp peaks, as seen during the Achaemenid and Hephthalite period, seem to indicate intense investment and expansion that ultimately appear to be unsustainable. The Hephthalite period in particular, is a significant peak above the Kushano-Sasanian and Islamic periods surrounding it, which are,

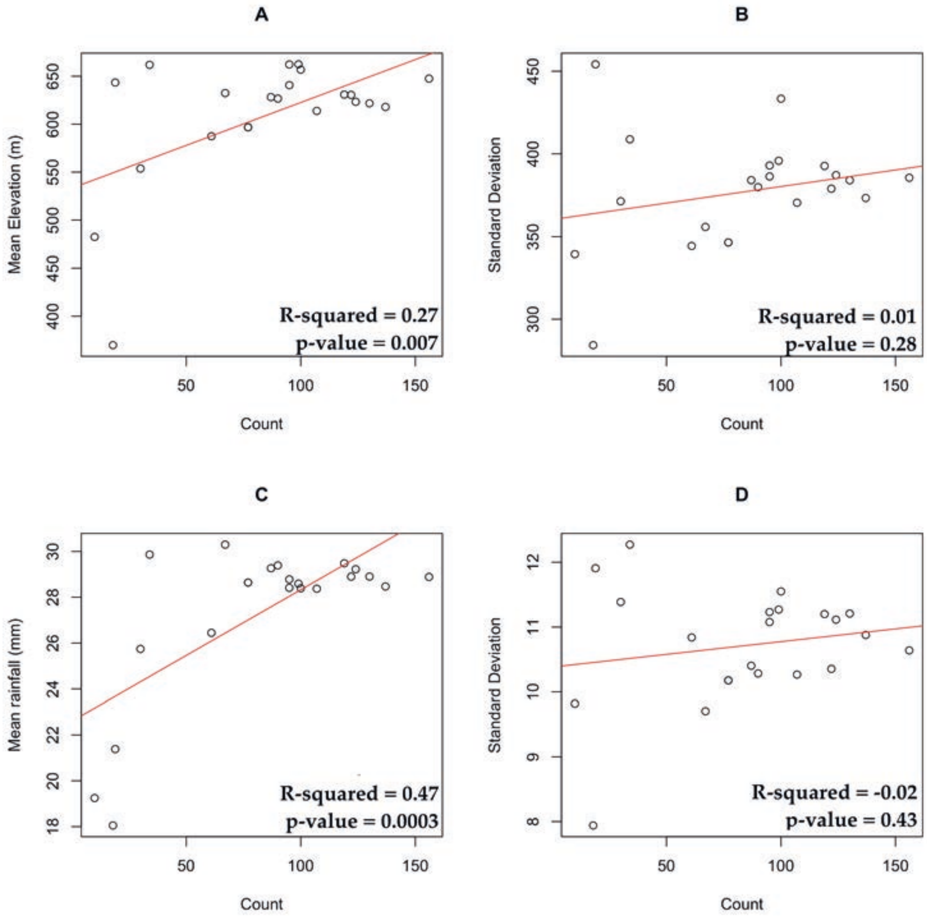

Figure 6. Plots showing relationship between environmental and topographic variables and site counts per period: (a) mean elevation, (b) standard deviation of elevation, (c) mean rainfall, (d) standard deviation of rainfall.

themselves, mostly above the site count average. Site counts during these latter periods (LS-GH) appears to show a return to levels last seen during the Hellenic periods, and more severe fluctuations that parallel the more frequent historically-attested conflicts that were prevalent in the region during these periods (Soucek 2000).

The significant drop in site counts during the Chaghatai period is particularly striking. While the severity of the Mongol and Chaghatai conquest during this period is not in doubt (Soucek 2000: 105-106; 121), the paucity of archaeological remains is also perhaps not surprising given the intent of conquest rather than settlement. The site counts during the subsequent Timurid period, while relatively modest, indicate that many abandoned or destroyed sites were quickly resettled. Unfortunately, it is not possible to evaluate the continuation of this rebound given the available data, as the archaeological scope of Ball and Gardin's (1982) *Gazetteer* ends during this Timurid period.

Bringing in environmental and topographic data adds further dimensions to this record. As stated, we predicted that periods of increased site count would correspond to both increased use of areas suitable for irrigated agriculture as well as exploitation of more marginal areas, while periods of low site count would be limited primarily to areas suitable for irrigated agriculture. Settlement density would be greater during periods of overall increased site count, and less during periods of low site count. This relationship is well supported by the data, showing a clear negative relationship between site counts and mean distance between sites (Figure 5a). Pair correlation function analysis also supports this, with minimum r values increasing as site counts increase (Figure 5b).

Looking at elevation and rainfall shows little evidence of significant patterns. The mean elevation of sites increases as site counts increase (Figure 6a), but much of the variation is unexplained by this variable. Variability, measured here by the standard deviation of elevation values of sites per period from the period mean, shows no significant relationship (Figure 6b). As site numbers increase, sites are not neces-

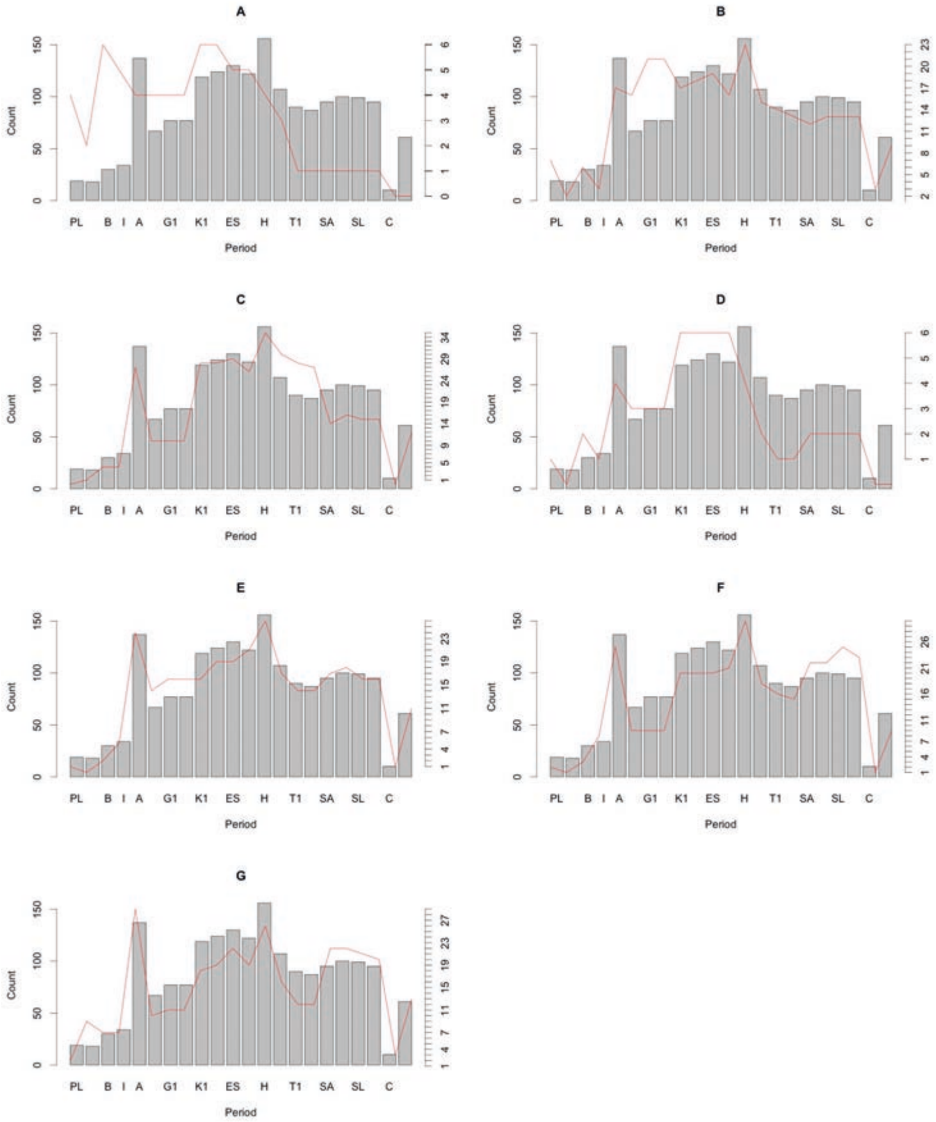

Figure 7. Graphs showing changes in site count per period (grey bars) against changes in occupation of Land Use/Land Cover areas (solid red line): (a) barren or sparsely vegetated, (b) dryland cropland and pasture, (c) irrigated cropland and pasture, (d) cropland/grassland mosaic, (e) cropland/woodland mosaic, (f) grassland, (g) shrubland.

sarily occurring in more topographically-varied areas. Mean annual precipitation (Figure 6c) shows a stronger relationship, with an increase in site numbers corresponding to expansion into areas of greater rainfall. Rainfall variability, again measured here by the standard deviation of rainfall values for sites per period, shows no relationship or trend (Figure 6d).

Sampling sites within land-use classifications adds further resolution to these changes in settlement pattern and identifies areas of significant occupation (Table 3). Per period, plotting site counts against sites per land-use types shows notable differences in the preference for certain areas during periods of increased site numbers, while also allowing for clearer detection of periods in which land-use occupation increases while site counts decrease. Barren or sparsely vegetated areas are apparently unaffected by changes in regional site counts, with occupation in these areas occurring during periods of both relatively high and low site counts (Figures 7a & 8a). Dryland cropland and pasture areas, on the other hand, have a strong positive correlation with site count (Figures 7b & 8b). Per period fluctuations in dryland cropland and pasture occupation follow overall regional trends of increases and decreases. The exception is a notable spike during the G1 and G2 periods, during which overall regional site counts decrease while dryland cropland and pasture occupation increases. Use of these areas decreases during the K1 period, despite the overall regional site count increasing. This spike is absent in irrigated cropland and pasture, which otherwise exhibits an even stronger positive correlation between site count and land-

Description	Count	R-squared	P-value
Dryland Cropland and Pasture	49	0.67	<0.0001
Irrigated Cropland and Pasture	48	0.83	<0.0001
Cropland/Grassland Mosaic	11	0.52	<0.0001
Cropland/Woodland Mosaic	53	0.93	<0.0001
Grassland	36	0.86	<0.0001
Shrubland	57	0.81	<0.0001
Barren or Sparsely Vegetated	17	0.001	0.32

Table 3. Land Use/Land Cover classifications with site counts and correlations values.

use occupation (Figures 7c & 8c). Increases and decreases in irrigated cropland and pasture area usage matches regional trends in site count increases.

Cropland/grassland areas demonstrate a moderately strong positive relationship with site counts per period and generally conform to regional trends through the KS period (Figures 7d & 8d). Beginning with the H period, usage of these areas decreases considerably and ceases entirely after the Chaghatai destruction, which to some extent mirrors the regional trends in site counts. Thus, increases in site counts during the SA-GH periods are matched by increases in occupation of these areas, though still remaining relatively scarce. In contrast, cropland/woodland areas show a much stronger positive correlation with regional site counts, while also following trends in site increases and decreases (Figures 7e & 8e). Whereas the highest number of cropland/grassland sites was seven, during the K1-KS periods, cropland/woodland areas had, on average, seventeen sites across all periods and as many as thirty-three during the Hephthalite period, during which cropland/grassland sites began to decline.

Grassland areas show a strong positive correlation with site counts and generally follow regional trends in site count fluctuation (Figures 7f & 8f). The only exception is a slight increase in grassland area occupation during the SL-GH period, while overall site counts decreased. Shrubland areas also exhibit a strong positive correlation with site counts, with increases and decreases mirroring changes in overall regional site counts (Figures 7g & 8g).

Discussion

We had predicted that increased site counts would result in greater use of irrigated croplands and expansion into marginal areas, while lower site counts would be mostly concentrated in irrigated croplands. The result of the above analyses show that irrigated cropland does indeed demonstrate a strong positive correlation with site counts, but remains high even during periods of population decline, such as during the LS-T2 periods (Figure 7c). Barren and sparsely vegetated areas, which we can define as the most marginal, remain largely unoccupied in general and otherwise bear little relationship to increases or decreases in site counts (Figure 7a). After the KS period, their numbers consistently decline and do not recover after the Chagatai period. Grassland and shrubland areas, which from an agricultural perspective are the next most marginal areas, actually have just as strong a positive correlation to site counts as irrigated cropland (Figures 7f-g). Up to the Hephthalite period, these areas generally follow overall trends in site increases and decreases, due to either parallel exploitation of irrigated and grassland/shrubland areas or exploitation because of over-exploitation of irrigated croplands. Both irrigated cropland and grassland/shrubland areas decline during the LS-T2 periods, suggesting overall demographic decline after the Hephthalite period. After the Hephthalite period, however, particularly during the Islamic SA-GH periods, exploitation of grassland and shrubland areas notably increases despite only slight growth in overall site counts and an actual decrease in irrigated cropland use. We interpret this reorientation as a change in subsistence or settlement strategies that favored these more upland areas, either for reasons of defense (difficulty of access and increased observation potential) or for pastoralism.

Other relatively marginal areas may be those classified as cropland/grassland mosaic and cropland/woodland mosaic (Figures 7d-e). They are classified as mosaicked because of their variability, being a combination of these various land classes. Cropland/grassland mosaic areas do not contain many sites, and perhaps for this reason do not demonstrate particularly insightful trends. They have a moderately strong positive correlation with site counts and peak during the Kushan periods. Cropland/woodland mosaic areas, on the other hand, demonstrate the stron-

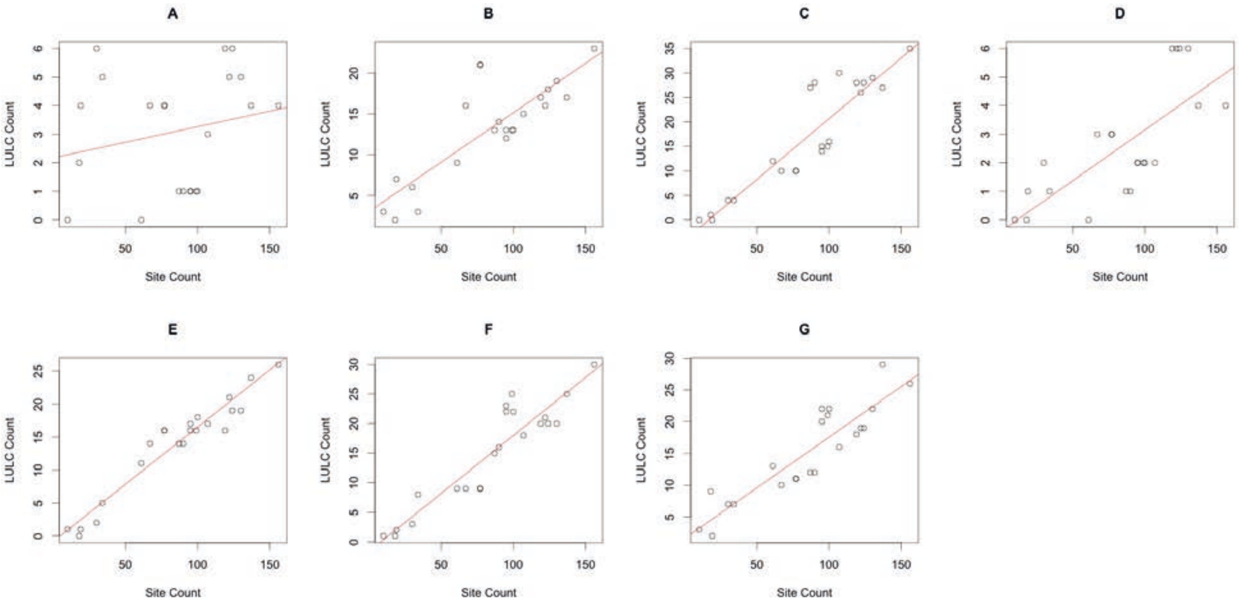

Figure 8. Plots showing linear relationships between Land Use/Land Cover occupation levels and overall regional site counts. See Table 3 for correlation values. (a) barren or sparsely vegetated, (b) dryland cropland and pasture, (c) irrigated cropland and pasture, (d) cropland/grassland mosaic, (e) cropland/woodland mosaic, (f) grassland, (g) shrubland.

gest positive correlation with site counts and mirror almost perfectly increases and decreases in overall regional site counts. These areas also see increased occupation during the SA-GH periods, while irrigated cropland declines. Assuming land-use characteristics today largely reflect conditions in the past, the high frequency of sites in these cropland/woodland areas and their continued exploitation during later periods, may be the result of this variability which allows for the exploitation of a wider range of resources during times of stress.

Dryland cropland areas were expected to largely mirror changes in irrigated cropland, which they do, albeit with a slightly less strong positive correlation. The most significant departure from regional site count trends occurs during the SE-G2 periods, where occupation of dryland cropland areas increases while regional site counts decrease. Use of irrigated cropland also decreases during this period, suggesting a greater focus on rain-fed agriculture as opposed to irrigated. From these analyses it is clear that the reputation of Bactria as the "land of a thousand cities," most prevalent in Greek and Roman sources, must actually be based on settlement during the Achaemenid or the Kushano-Sasanian periods, rather than during any period of Hellenic occupation (Leriche 2007). While the paucity of material during the Bronze and Iron Ages can, on one hand, be attributed to the lack of focus on these periods by archaeological projects or the difficulty in identifying diagnostic material from these periods, the long-term effects of Achaemenid investment and development should not be undervalued. Investment in the region in terms of irrigation, demographic growth, and migration likely paid off in terms of providing the infrastructure necessary to encourage and support increased settlement in low-land irrigated areas (Rapin 2007: 35). The shift away from irrigated cropland towards dryland cropland is thus quite surprising, assuming that the irrigation infrastructure constructed by the Achaemenids remained largely intact during these periods. Irrigated agriculture was rare in ancient Greece and Macedonia, from which many settlers to Bactria had come (Mairs 2014: 38-39). Increased use of dryland cropland during these periods may then be the result of an interest of these settlers in occupying new, non-Achaemenid areas, and maintaining agricultural practices familiar to them from their homelands.

First order effects are therefore significant in the land use history of this region, with different land use/land cover classes having major influences on the presence and magnitude of occupation during different periods. Second order effects are also notable, however, and our prediction that site density would increase with site count is demonstrated to be largely true. Figure 5a shows a negative, though non-linear, relationship between the mean distance between neighboring sites and overall regional site counts, while Figure 5b generally shows the same trend. The exception, again, is during the SA-GH periods where the minimum distance at which sites are most clustered increases to larger distances, despite site counts being relatively low. The combination of this increased minimum distance with a reorientation towards grassland and shrubland areas during the SA-GH periods indicates significant changes in land use at this time that occurred in tandem with an increase in site count and expansion.

As discussed previously, there is always the risk that archaeological surveys over-represent certain periods, thus creating artificial spikes in site frequency or size that do not accurately reflect the settlement history of the region. Given the variability in the data that Ball and Gardin (1982) synthesize in their work, regional site counts appear to be quite consistent and generally demonstrate the long-term patterns expected based on historical sources. Thus, while site counts dropped substantially after the Achaemenid period, the levels they dropped too would become a more or less consistent baseline from which counts would increase, sometimes significantly, during later periods of investment and development. It is also worth noting that the periodization employed in this paper is not equal in terms of duration. The Bronze Age period itself covers as much time as the next fourteen periods, and likely experienced significant fluctuation within that time. Yet it is only through comparison to later time periods that the overall magnitude of changes between periods can be contextualized and multi-period trends in land use and site occupation can be identified.

Conclusions

The archaeological record of Bactria is understudied as a whole, and when studied often limited to specific periods or cultures. By making use of all the data and periods available to us from Ball and Gardin's (1982) Gazetteer, we demonstrate the value of taking such a broad diachronic and spatial approach. General models of settlement pattern and organization that predict relationships between land use and site count, such as the IFD, are shown to be useful frameworks within which much of the variety in the data can be explained. Deviations from this model are, however, also more noticeably evident when using these models and can be better explained through the examination of first and second order effects that consider exogenous and endogenous factors influencing the placement of sites. The results presented here are necessarily preliminary due to the nature of the data and scope of this paper. Yet we consider these results promising, and believe that they can be further improved through integration of larger datasets to increase site counts, and more consistent data that can add further resolution by breaking down what kinds of sites are increasing or decreasing in usage. While this study homogenized all sites to be generic, in reality the sites used here represent a variety of functions that, upon further investigation, will serve to provide a more nuanced understanding of the Bactrian landscape over time.

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Unravelling Urban Religious Landscapes: Visualizing the Impact of Commerce on Religious Movement at Ostia

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Abstract

Ritual activity constitutes one religious practice that pervaded ancient cities like Ostia, Rome's ancient port. Despite the extensive surviving evidence at Ostia for religious practice, the ways in which the urban landscape shaped religious movement has not received previous attention. This article focuses on how economic activity may have helped to structure areas of ritual movement throughout the city. Using the Urban Network Analysis Toolbox developed for ArcGIS, areas of economic activity are studied by applying betweenness centrality to determine 'hotspots' of movement. These 'hotspots' can be used as nodes for undertaking further study of processional movement. The preliminary results suggest that the proposed methodology can enrich archaeological investigations into ritual movement and religious landscapes.

Keywords: urban network analysis, GIS, human movement, spatial analysis

Introduction

The idea that urban and social landscapes have an impact on religious activity underlies a number of studies focused on religious movement (e.g., Demarest 2006; Popkin 2016). Scholars have long recognized the relationship that existed between social meaning and the built environment (e.g., Giddens 1984) and the ways in which these shaped patterns of interaction (Lawrence and Low 1990; Rapoport 1977). The spatial organization of a city not only structured daily exchanges between people but affected how ritual or religious activities interacted with the cityscape and its inhabitants (Moore 1996). The potential of studying ritual movement has only recently garnered attention. Early research into past landscapes saw movement as secondary in importance within phenomenological based studies (Tilley 1994) whereas movement is now recognized as a central component for a city's organization and its subsequent analysis (Álvarez and Oubiña 2007; Paliou, Lieberwirth, & Polla 2014). Movement within the cityscape was shaped by a variety of different factors, ranging from the pre- existing street network, movement intent, urban activity, and the built environment (Giddens 1984; Russell 2016). How movement can be studied within the context of an ancient city and the ways in which it informs our understanding of social practices has resulted in an influx of recent studies (Laurence 1994; Östenberg, Malmberg, & Bjørnebye 2015; Poehler 2017). Current methods for examining movement and the reciprocal relationship that exists with the built environment provides the context for undertaking the present study of ritual movement.

Considering the city of Ostia, Rome's ancient port, this paper explores how a specific aspect of the built environment, indicative of different types of social activity, may have impacted processional movement. In particular, it discusses the potential of applying an urban network-based approach using betweenness centrality measures to investigate the possible correlation between Ostia's commercial spaces and ritual movement. Specific processional routes at Ostia are unknown within the archaeological and historical record. By questioning how one form of social activity influences ritual movement, which is represented within the built environment through recognizable architectural structures, "influences ritual movement" can hypothesize about which areas of Ostia may have seen processional activity if influenced by commercial activity. This builds upon previous pedestrian-based studies, like Hillier and Hanson's (1984) model of space syntax, in order to provide new insight into a religious landscape that encompassed the entire cityscape.

Research Background: Ritual Activity at Ostia and Movement Studies

Ostia's Religious Landscape

The temples, shrines, and religious artefacts uncovered at Ostia provide a rich source of information about the city's religious life. Inquiry into temples and cultic practices remains one of the most contested areas of Ostian scholarship over the past decade (Pavolini 2016: 201). Until recently, studies were predominantly confined to individual temples or cults without considering their placement within the total cityscape (Squarciapino 1962; Taylor 1912). Recent scholarship has attempted more general investigations into the city's religious space (Arnhold 2015; Rieger 2004; Steuernagel 2004), while acknowledging the importance of Ostian rituals and their need for further study (Bruun 2009). How ritual activities, like processions, contribute to our understanding of Ostia's religious environment have not been adequately addressed. The numerous debates about the identification of individual temples do not shed light on the ways in which religious practices intersected with the city's residents (Van der Meer 2009).

The lack of existing information, either archaeological or literary, alluding to the nature of processional rituals at Ostia has resulted in minimal discussion of their presence within the city. While processions constituted a regular component of ritual practices, ancient authors rarely describe processions in detail, likely because they formed a standard part of the city's landscape and did not necessitate further commentary (Flower 1996: 97). Processions were ephemeral events, with their occurrence predominantly held in the memories of those who attended or heard about the event while leaving little to no lasting impression within the archaeological record (Connelly 2011: 314; Russell 2014). Existing discussions of Ostian processions focus on either the construction of a processional route that was structured by the spatial location of early temples (DeLaine 2008: 101) or their probable occurrence along Ostia's major streets (Boin 2013: 75). Undertaking new study of processional movement presents an unexplored method of looking at how religious practices were disseminated across the city. Directing enquiry away from identifying particular Ostian rituals and movement routes to considering what influenced processional movement more generally is one way to address the issues inherent in Ostian processional studies.

Movement Studies within Roman Archaeology

The formal study of human movement has been a popular avenue for archaeological research. Within studies of Roman urbanism, approaches to movement have predominately developed out of Pompeian research. These studies consider urban movement either in terms of proxy data or through the application of urban theories like space syntax. Early research focused on archaeological indicators of movement such as the presence of wheel ruts (Poehler 2006; Tsujimura 1991) or how architectural structures like street-side benches helped to structure pedestrian movement (Hartnett 2008). An alternative approach widely used is space syntax, which consists of a set of theories and methods initially developed for urban planning to explore the relationship between space and human society (Hillier 1996; Hillier and Hanson 1984). In relation to a street network, their methodology contends that a street's spatial arrangement is related to various social phenomena including movement flows. In particular, space is defined by its position in relation to other spaces within a city. Space syntax has been applied to archaeological contexts to explore the characteristic of both individual buildings as well as urban street systems (Grahame 2000; Laurence 1994; Stöger 2011).

Axial analysis, developed by Hillier and Hanson (1984), has commonly been applied in order to study the spatial configuration and movement potential of ancient street systems (Kaiser 2011; Stöger 2011). In this instance, the street network is modelled topologically in order to identify which street segments are more accessible and therefore saw greater use (Hillier and Hanson 1984: 82–142). The analysis first represents the street in terms of axial lines, which consist of the longest and fewest lines that can be drawn within the open spaces of a street that often correlates to lines of sight. These lines are then converted to a connectivity map where nodes represent streets and links represent intersections (Porta, Crucitti, & Latora 2006b: 854). The distance between each node provides an index of its connectivity to every other node in the system and which can be used to calculate various space syntax metrics. The outcome of axial analysis is a visualization produced on a colour scale of red to blue that indicates which axial lines, corresponding to streets, are most integrated within the network, providing an indication into likely areas of movement.

While space syntax is useful in determining how a city's street network design promoted movement, it does not account for how the space was actually used or other urban or social activities that influenced movement (Batty 2003; Benedikt 1979; Ratti 2004; Steadman 2004). Furthermore, it cannot account for specific types of movement or movement intent within a street network. This poses issues when trying to address how processional movement can be studied within the ancient city when routes are unknown. Processions have a particular purpose when traveling through the streets of a city, an intent that cannot be properly accounted for within space syntax models.

One way to address the difficulties of movement intent is to question what factors influenced movement directionality. Processional movement had an underlying purpose, to move from point A to point B. And while movement was not the only purpose of a procession, this allowed the ritual to be seen and experienced (Grimes 1992: 72). Current studies of ritual movement highlight that a close relationship existed between urban space and the construction of sacred routes (Lawrence and Low 1990; Popkin 2016). In many instances, a landscape or city had certain attractors that helped to guide and structure processional routes (Kristensen and Friese 2017; Malville and Malville 2001; Morton et al. 2014). In particular, looking at how commercial activity affected ritual movement, or vice versa, enables us to question how a specific form of urban activity may have structured possible areas of ritual movement. This is far from the only factor that would have impacted ritual movement, but the focus on commercial activity is used as a way to think about how processional routes were formulated within the city and how this form of movement can be studied.

By the 2nd century AD Ostia had a rich commercial landscape, ranging from large warehouses (*horrea*), areas of production like granaries, and small shops (*tabernae*). Ostia's streetscape in particular was characterized by shop fronts, with an estimated 800 *tabernae* located across the city (DeLaine 2005; Ellis 2011). Shops, warehouses, and areas of production define Ostia's commercial spaces, reflecting three distinct types of commercial activity. Three categories are used within this study for the purposes of simplicity and to show the potential of the proposed method. The complexity of defining commercial space at Ostia cannot be negated. Consideration of how these different commercial spaces either encouraged or deterred movement sheds new light on possible areas of processional movement at Ostia. While the potential of undertaking a movement-based study at Ostia has previously been addressed through space syntax analyses (Kaiser 2011; Stöger 2011), it has yet to be applied to the study of processional movement. The street network and existing architectural landscape at Ostia provides a unique opportunity to consider how commercial activities, structured by the built environment, may have regulated processional movement. This presents a novel approach to examining a specific form of movement within the ancient cityscape.

Urban Network Analysis of Commercial Spaces at Ostia

The application of network science approaches to archaeological studies has seen considerable attention in recent years (Brughmans 2013; Brughmans, Collar, & Coward 2016; Knappett 2013). In particular, network analysis has been applied as a quantitative approach to study the topology and movement structure of cities using methods like space syntax (Hillier and Hanson 1984; Porta, Crucitti, and Latora 2006a). As previously discussed, however, several issues limit its application to the study of processional movement. As a result, a new form of network analysis is employed as a way to address some of the issues implicit within space syntax by focusing on how commercial activity, recognizable by specific architectural structures, effects movement.

Urban Network Analysis Toolbox & Betweenness Centrality

Recognizing the above limitations for studying processions, the present study applies an innovative approach to studying urban movement patterns using the Urban Network Analysis (UNA) toolbox in ArcGIS, created by Sevtsuk and Mekonnen (2012). Unlike axial analysis within space syntax which only looks at the geometric design of a city's street network, this toolbox implements a third metric for considering movement patterns along a street network, the built environment. The urban landscape is modelled using three elements within the ArcGIS toolbox: edges (streets), nodes (intersections), and buildings. This tripartite network enables buildings to become the focus of analysis, enabling a new understanding about the fundamental relationship that existed between urban activities and the study of movement along a city's street network. Buildings can be prescribed various attributes that range from their total size to their urban function. This enables the different properties of individual buildings to be studied within the context of both their spatial position within the city as well as how they may have affected movement along a street network. The size of the study area can also be specified, correlating to different forms of movement (e.g., pedestrian or vehicular).

Additionally, innovative is the fact that all calculations occur within ArcGIS 10.0–10.3, presenting new possibilities for undertaking various urban spatial analyses. This negates previous issues of having to undertake network analysis in a separate software program (e.g., Pajek, Visone, Gephi) and importing the results into a GIS platform in order to visualize the results (Andris 2016). This toolbox allows for the calculation of the most common network centrality measurements directly within ArcGIS: reach, gravity, closeness, betweenness, and straightness (Sevtsuk, Mekonnen, & Kalvo 2016).

Centrality measurements are one of the primary network analysis functions used by urban planners to determine areas that are related to increased pedestrian access (Wilson 2000). For considering movement potential in relation to commercial spaces at Ostia, the present article applies betweenness centrality, which computes the probability that a certain node or building will be passed when travelling the shortest distance between two points (Isaksen 2013: 61). While this is not the only measure that can be used to address movement along a city's street network, it presents a visual indication into potential movement patterns corresponding to passing specific commercial structures. Since the actual processional routes are unknown, this specific centrality measurement provides an indication into certain areas that may have been passed, regardless of the start point or destination, rather than attempting to define actual routes. The UNA toolbox applies a betweenness centrality equation adapted from Freeman (1977) whereby commercial buildings are considered based on their likelihood of being passed by movement along Ostia's street network (Sevtsuk, Mekonnen, & Kalvo 2016: 14).

Betweenness is not an indication of the ease of a potential movement route, but indicates whether or not a building will be passed (Isaksen 2012: 62). Assessment of betweenness centrality is important because it provides an indication of which commercial structures had greater control over structuring movement within Ostia's street system within the framework of the present study (Freeman 1977: 35). In terms of movement patterns, betweenness is often associated with higher traffic volume or bottlenecks; meaning that a building with a higher betweenness value indicates that it had a more important role within the city's total infrastructure. More importantly for the present study, it presents the potential of being passed by through-traffic, providing insight into how commercial structures have the potential for generating movement.

The application of betweenness centrality in relation to Ostia's different commercial buildings presents an innovative approach to looking at how commercial activity may have helped to structure areas of ritual movement. As the commercial structures are weighted relative to their assumed importance, betweenness measures provide an indication of areas most likely to be passed. The resulting values constitute 'hotspots', or areas that can be used to help inform our understanding about commer-

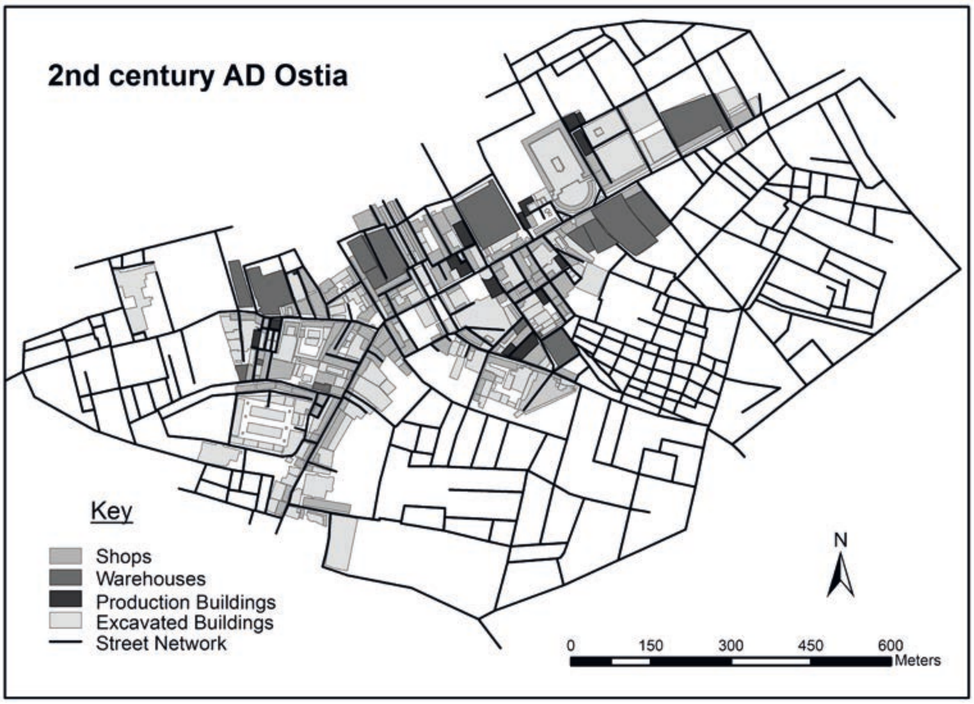

Figure 1. Ostia's 2nd century AD built environment showing commercial building classifications and the extended street network (after Calza 1953; Mannucci 1995).

cial areas of the city possibly passed by processional rituals.

The Model

In order to examine what impact commercial spaces may have had on ritual movement, a model (Figure 1) of the city during the late 2nd century AD was first digitized within ArcGIS following the original plans of Calza (1953) and the updated map created by Mannucci (1995). The street network that extends beyond the excavated city is additionally included after the preliminarily geophysical survey results undertaken by Heinzelmann (1998; Martin and Heinzelmann 2000) and the space syntax axial graph produced by Stöger (2011) following these results. It needs to be noted that portions of this extended street network likely postdate the period under consideration, however, since the final results are still awaiting final publication it was not possible to differentiate all the streets specific to the late 2nd century AD from the current plan. The extended street network's inclusion accounts for the potential of movement travelling in and out of the city rather than confining analysis to only the excavated city, helping to negate the issue of edge effects.

Three different types of commercial spaces (shops, warehouses, production spaces) were then classified within the late 2nd century AD city. Regarding these classifications, the complexity of trying to define individual spaces within the ancient city cannot be discounted. This presents just one interpretation following previous scholarship on the definition of commercial spaces throughout the city (DeLaine 2005; Rickman 1971). Due to how the city has been excavated and studied, it is difficult to identify each commercial space with accuracy. In many instances, the size and location of a structure along the street network has informed our definition of a commercial space where there is limited existing archaeological material. The different space classifications serve as the focus of analysis within the UNA toolbox applying betweenness centrality measurements as an exploratory approach for studying ritual movement.

Metric Radius

The study radius must first be determined in order to set the scale at which movement will be assessed within the city. The input radius specifies the network radius for which the betweenness calculations occur (Sevtsuk and Mekonnen 2012: 292). If a radius is not specified, then the measurements are computed for an infinite radius that can reach all structures within the graph. For example, if a 100 m radius is used, then movement will be calculated for each building relative to every other building located within a 100 m network radius. To determine what

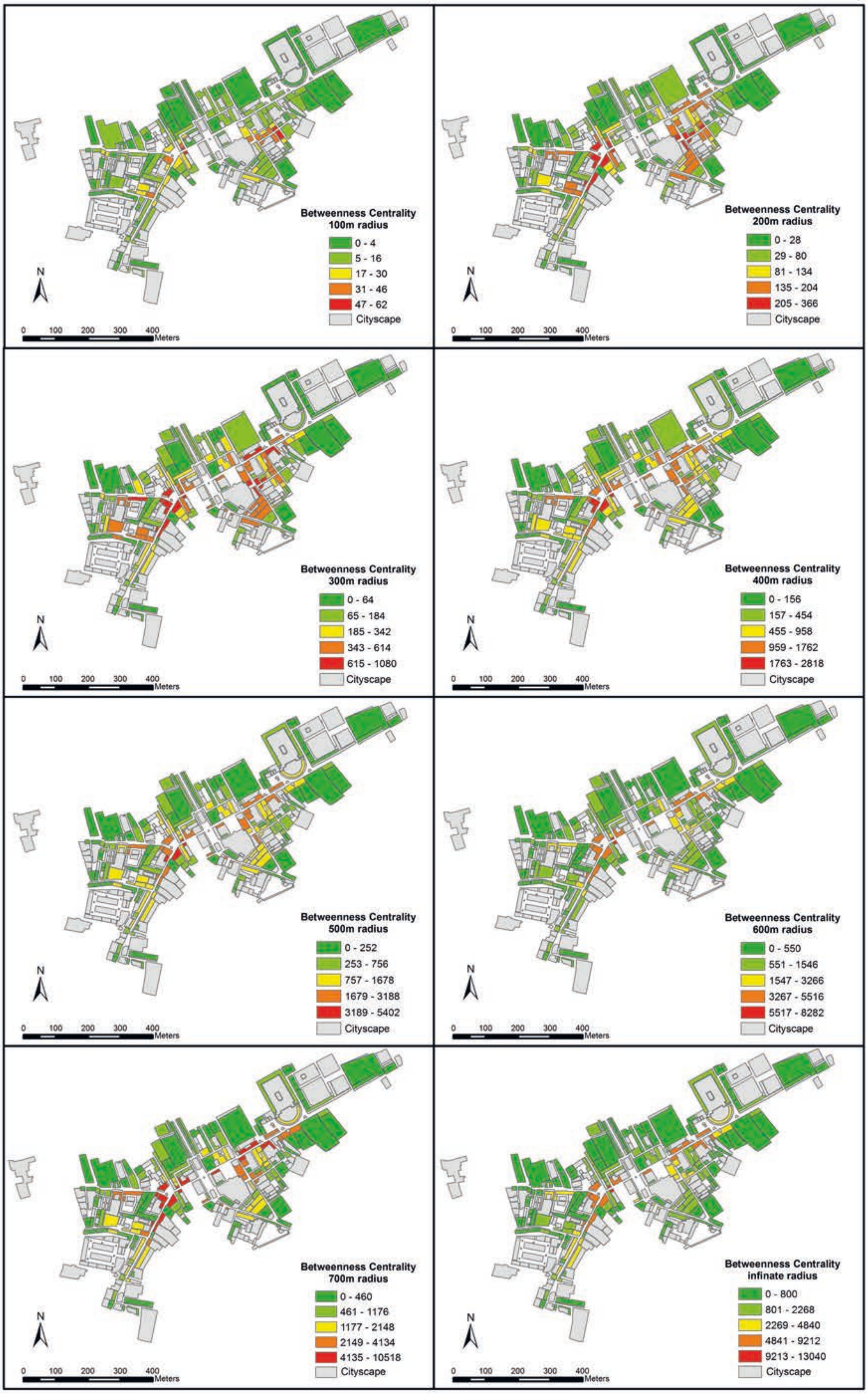

Figure 2. Image showing change in betweenness centrality with different radii values.

radius should be applied to the present study, Ostia's commercial landscape and extended street network was examined with eight different metrical radii (100–700 meters and infinite). Betweenness centrality was calculated in relation to each radius based on unweighted buildings to address the correlation between betweenness centrality and movement radius. The radius affects the network calculations in that each commercial space is considered only if it is an equal or less geodesic distance than the specified radius from every other building within the network (Sevtsuk and Mekonnen 2012: 292). The difference in radii is shown below (Figure 2) in relation to the 182 commercial spaces. The graphs are represented on a colour scale from red to dark green, with red indicating spaces of the highest betweenness centrality or areas most likely to be passed and dark green as areas of the lowest betweenness centrality.

Figure 2 shows that there is considerable variation in betweenness centrality values when the radius is adjusted. Local pedestrian movement is generally best accounted for with a 400 m radius, while a 800 m radius tends to correlate to vehicular movement (Omer, Rofè, and Lerman 2015). Within the present calculations, a 300–400 m radius shows the best average of the two highest betweenness centrality measures, displayed in red and orange (Figure 2), located throughout the city. A 400 m radius is ultimately used throughout this study because it accounts for movement within a greater portion of the cityscape. In relation to pedestrian movement, this associates to movement potential across the majority of Ostia's excavated environs. The application of a smaller radius (e.g., 100–300 m), alternatively, could be used for exploring smaller ritual movement areas, such as those confined to neighbourhoods rather than city-wide processions.

Weighting of Commercial Buildings

One of the most innovative features of the UNA toolbox is the ability to weight commercial spaces based on pre-determined values such as occupancy, importance, or size. The present study attributed each commercial space a weighted importance value 0, 50, or 100. The exact combination of weighted values is arbitrary. The choice to use intervals of 50 serves to more clearly differentiate between the three different commercial space classifications. The resulting betweenness calculations present a visualization of which commercial areas of Ostia had the highest movement potential weighted by building importance. Since the extent to which different commercial spaces influenced processional movement is unknown, three different iterations of building weights are run to determine how weighting the three commercial spaces in different ways effected movement potential across the cityscape. The highest betweenness values are displayed in red, indicating the greatest movement potential while dark green indicates the lowest movement potential areas. The following graphs (Figures 3–5) illustrate the difference in betweenness centrality for weighting shops, warehouses, and production areas each with an importance value of 100 while the other two classifications are given lower values.

The results indicate that the alteration of weights for different commercial classifications has a significant impact on the betweenness calculations and movement potential. The greatest difference in movement potential is shown with the last figure (Figure 5), where production areas were weighted highest and shops lowest. This is important because it indicates how areas of processional movement could change based on attraction or aversion to going past differing commercial spaces. While all possible weighted combinations are not presented, the three images above (Figures 3–5) show that weighting commercial structures in different ways following their importance for ritual movement illustrates differentiation in areas of likely movement passage throughout the city. This provides an initial indication into how activity occurring within the built environment impacted where ritual movement may have travelled.

Discussion and Conclusions

The calculation of betweenness centrality in relation to commercial structures begins to address the issue of how movement intent can be studied within the ancient city. The present focus has questioned how different commercial spaces may have played a role in structuring ritual movement patterns at Ostia. This moves beyond previous studies of movement at Ostia focused solely on how the street network design generated movement (Kaiser 2011; Stöger 2011). The

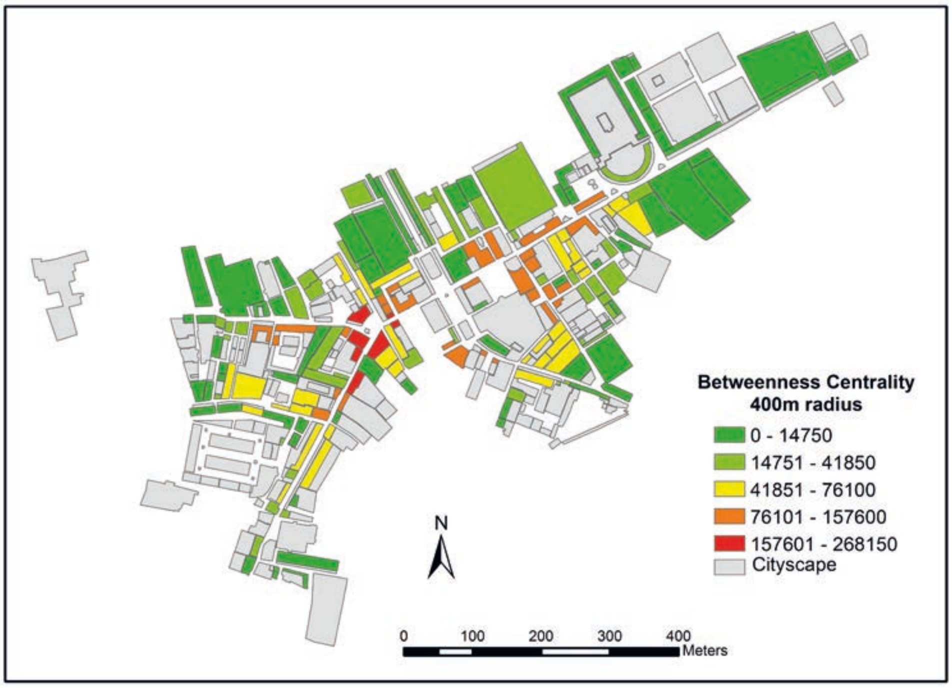

Figure 3. Betweenness centrality of commercial spaces within a 400m radius with the following building weights:
shops – 100;
warehouses – 50
production – 0.

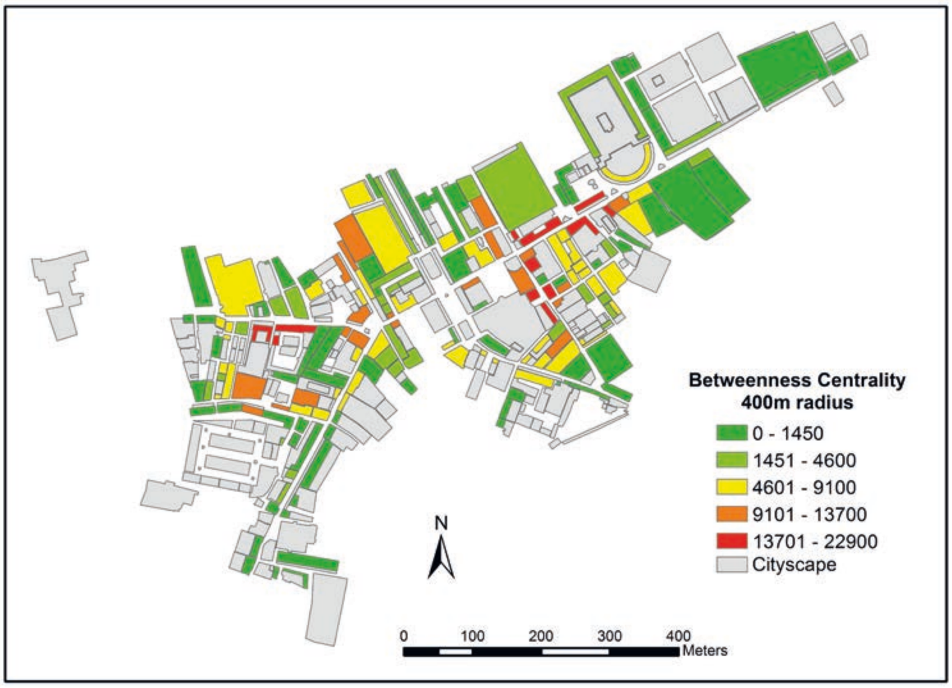

Figure 4. Betweenness centrality of commercial spaces within a 400m radius with the following building weights:
warehouses – 100;
production – 50;
shops – 0.

results of the weighted betweenness centrality calculations illustrate that changes in how commercial buildings were weighted based on their supposed importance for ritual activity had a visible correlation to movement potential. The most important aspect is that multiple types of commercial buildings can be included, an aspect that can broaden future analyses to include other types of urban spaces.

The implications of these betweenness calculations results in what can be termed 'hotspots' of movement. The two highest betweenness centrality measures shown in Figures 3–5 indicate areas with a high degree of movement potential relative to different commercial spaces. In relation to ritual movement, these hotspots indicate certain areas that would have been passed if the highest weighted space was important for a specific ritual. The results do not indicate full areas of movement, rather, they indicate

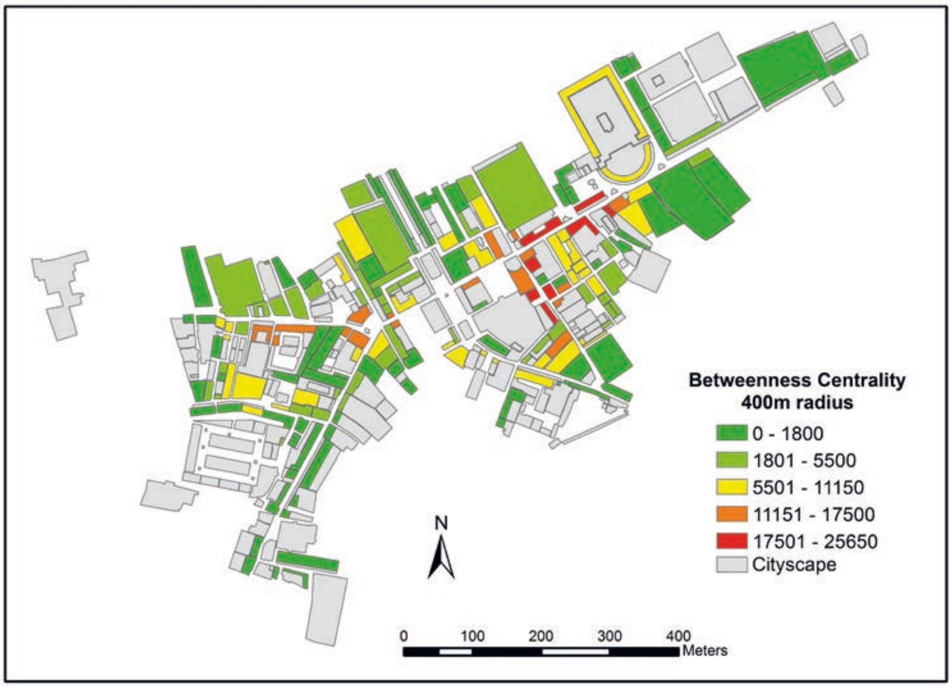

Figure 5. Betweenness centrality of commercial spaces within a 400m radius with the following building weights: production – 100; warehouses – 50; shops – 0.

possible nodes within the city that could have been passed by a procession, providing a framework for future study about the influence of commercial activity on processional movement at Ostia. By taking into account the specifics required for a particular procession, such as avoiding a specific temple or area within the city, the movement potential results can be adapted for individual routes. The examination of different iterations of building weights enables various models to be generated that visualize the ways in which commercial activities affected movement routes. Most importantly, this creates a way to begin to think about how ritual movement can be studied by questioning what affects different movement routes.

The network analysis computed in relation to commercial spaces at Ostia presents the first attempt at visualizing how commercial activity affected religious movement. The understanding of how urban and social factors structured ritual movement furthers our understanding of both processional routes and the larger religious landscapes they constructed at Ostia. While the specific routes are not detailed, potential areas are visualized that set the foundation for future more focused studies of ritual movement. The benefit of this method is that it considers how movement intent can be approached, moving away from more general models of pedestrian activity. The dynamics of the built environment and social activity are accounted for within the model, allowing new insights that expand upon previous space syntax results of movement directionality at Ostia. This presents just one method for exploring the potential of studying a specific form of pedestrian movement. An advantage of applying betweenness centrality within the UNA toolbox is not only the compatibility with ArcGIS, but also the addition of the built environment within the model. It provides a visualization of how urban structures shaped movement potential.

The study of processional movement and commercial spaces at Ostia adds a new dimension to ritual studies. The methodology not only forces the researcher to think about how urban activity can be classified in relation to the built environment, but it allows us to ask questions about how this activity helped to shape ritual movement practices. The UNA toolbox for applying betweenness centrality has significant implications for not only studying ritual movement but allows for other spatial questions to be addressed. The ability to adjust the model to different focuses of analysis enables many new questions to be raised, not just specific to ritual movement.

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Modelling Acoustics in Ancient Maya Cities: Moving Towards a Synesthetic Experience Using GIS & 3D Simulation

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Abstract

Archaeological analyses have successfully employed 2D and 3D tools to measure vision and movement within cityscapes; however, built environments are often designed to invoke synesthetic experiences. GIS and Virtual Reality (VR) now enable archaeologists to also measure the acoustics of ancient spaces. To move toward an understanding of synesthetic experience in ancient Maya cities, we employ GIS and 3D modelling to measure sound propagation and reverberation using the main civic-ceremonial complex in ancient Copán as a case study. For the ancient Maya, sight and sound worked in concert to create ritually-charged atmospheres and architecture served to shape these experiences. Together with archaeological, iconographic, and epigraphic data, acoustic measures help us to (1) examine potential locations of ritual performance and (2) determine spatial placement and capacity of participants in these events. We use an immersive VR headset (Oculus Rift) to integrate vision with spatial sound and sight to facilitate an embodied experience.

Keywords: acoustics, GIS, ancient Maya, 3D modelling, immersive virtual reality (VR)

Introduction

The acquisition of large and comprehensive data sets using, for example, airborne LiDAR is changing our perceptions of ancient landscapes, and importantly encouraging fresh lines of enquiry (e.g. Chase et al. 2014; Prufer, Thompson, and Kennett 2015; von Schwerin et al. 2016). Diverse methodologies employing space syntax, Geographic Information Systems (GIS), and network analysis are used to carry out investigations of ancient cities (e.g. Brughmans 2013; Landau 2015; Parmington 2011). Several archaeological analyses have successfully employed 2D and 3D tools to develop computational methods to measure visibility and movement to enrich our understanding of ancient landscapes (e.g. Dell' Unto et al. 2016; Llobera 2007; Paliou 2014; Richards-Rissetto and Landau 2014; Richards-Rissetto 2012, 2017a, 2017b; Sullivan 2017).

Archaeoacoustics—the study of sound in archaeological contexts—is now becoming more commonplace, particularly to complement phenomenological approaches (e.g. Cross and Watson 2006; Feld and Basso 1996; Helmer and Chicoine 2013; Mlekuz 2004; Rainio et al. 2017; Tilley 1994).

To contribute to this growing body of knowledge, we investigate the question: What roles did sound potentially play in the urban dynamics of ancient Maya cities? As a case study, we employ GIS, 3D modelling, and Virtual Reality (VR) to model acoustics in the main civic-ceremonial complex at the ancient Maya city of Copán in Honduras. Our approach seeks to take advantage of both computational and embodiment methods. The computational component provides quantitative data on sound propagation and reverberation time and the experiential component uses these data to create spatial audio in VR. The two-prong approach involves three components:

1. The Spread-GIS toolbox for ArcGIS to calculate noise propagation in Copán's city center.

2. The 3D modelling software SketchUp Pro to calculate building capacity and reverberation time for interior spaces.

3. The gaming engine Unity3D and the Dear-VR plugin to create a VR prototype environment with appropriate spatial sound.

To investigate the potential role sound played in urban dynamics at Copán, we situate the resultant GIS and 3D modelling data within a framework of proxemics—a concept examining the impact of space and distance on human interaction. In regard to sound, different distances between speakers and audience are associated with different methods of communication that provide information on cultural uses of space (Hall 1969; Moore 1996). For example, among the ancient Maya, data on acoustics can inform on the position(s) of a ruler during ritual events in relation to different audience members offering insight into the role Maya ritual practices played in establishing, maintaining, and transforming social relations (Sanchez 2007; Schele and Miller 1997). In our case study, we perform preliminary comparisons of acoustics between two locations in Copán's main civic-ceremonial complex—the accessible, public Great Plaza and the restricted, private East Court—two important spaces transformed by Ruler 13 in the early eighth century (Figure 1).

Ancient Maya Synesthesia—Vision and Sound

The senses were particularly important in ancient Mesoamerica. The ancient Maya regarded the senses as invisible phenomena that invested life and meaning to spaces. Synesthesia, which is the release of one sensation through another, was integral to the ancient Maya. Visual imagery could lead to sensations associated with hearing. Maya art and architecture was a means of sensory communication as was writing. Evidence suggests scripts were meant to be read aloud, and that writing was a device for vocal readings or performance—thus intricately linking the senses of sight and sound (Houston et al. 2006).

Sensory organs like eyes were believed to possess a form of agency; sight, illustrated by iconography of projective eyeballs, served a projective role in ancient Maya society—what you saw affected what you did (Houston et al. 2006). Visibility studies have been done on regional and city-scale levels in the Maya region, illustrating that visibility served as a cultural mechanism to send messages to targeted audiences, establish boundaries, foster social cohesion, and send messages of power (Anaya Hernandez 2006; Doyle et al. 2012; Hammond and Tourtellot 1999; Richards-Rissetto 2010, 2017a, 2017b). While these studies add to our knowledge of experience and interaction among the ancient Maya, they leave out another important sense—sound.

Speech and song scrolls depicted in ancient Maya artwork communicate the importance and properties of sound. Sound was perceived as something concrete and the whiplash motion in the scrolls may represent the changing volume of speech. Music aroused deities, guided a dancer's rhythm, induced trance through repetition, mimicked animal calls, and enhanced the sensory experience (Houston et al. 2006). Sound and music were essential components of ritual—songs represented beauty, marked spaces as divine, and communicated information (King and Santiago 2011; Moore 2005; Sanchez 2007). Hieroglyphs often associate deities with music; for example, the storm god Chaak (associated with thunder and wind) is linked to song and music. Moreover, echoes or vibrations of sound have been artistically depicted in glyphs, showing an understanding of sensory stimuli (Houston et al. 2006).

Paintings, such as the Bonampak murals, depict trumpeters, drummers, and other musicians taking part in processions. Similar depictions are found on a mural fragment from the site of Las Higueras. These murals depict rattlers and flautists closer to their audience and drummers and trumpeters positioned further away, reflecting a sophisticated understand-

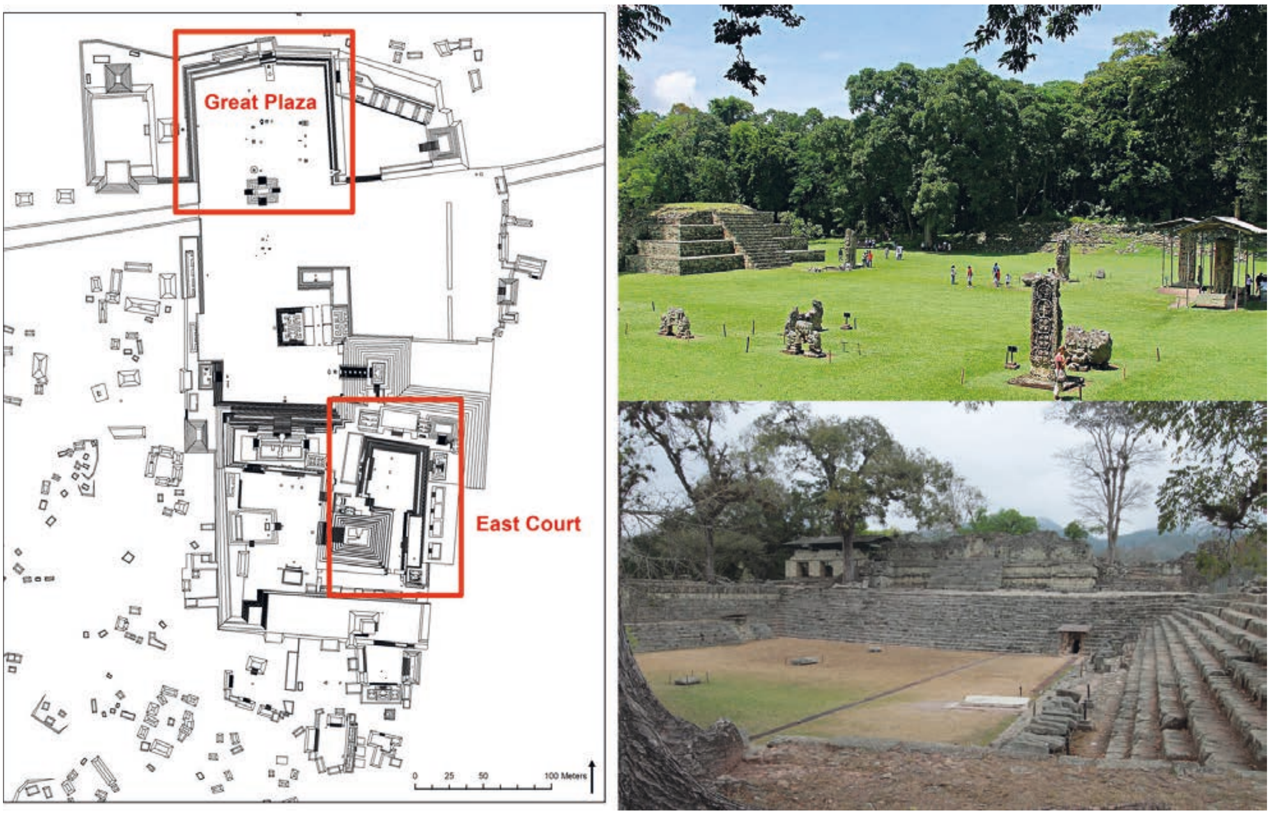

Figure 1. Main civic-ceremonial complex at Copán, Honduras (Great Plaza (top right); East Court (bottom right)).

ing of musicology where instruments with higher treble should be closer to the audience, while drums and other instruments with higher bass should be placed in the back (Houston et al. 2006). Additional archaeological evidence exists in the form of musical instruments, including shell trumpets, ceramic whistles, and wooden drums.

While musical instruments at the site of Aguateca are primarily found in elite contexts, instruments are also found in non-elite houses, suggesting music was not limited to a single social class (Stockli 2007).

The sonorous qualities of raw materials were also important in Mesoamerica. Clays, metals, and precious stones were selected for specific sound and color producing qualities in Postclassic Oaxaca. Moreover, clothing was often embellished with sound producing beads, pendants, and bells (King and Santiago 2011). Together, these lines of evidence indicate that sound was an essential component of ancient Maya life, but how did sound work in conjunction with different places, architecture, and material culture to differentially affect audiences, their experiences, and the messages they received?

Case Study—Ancient Maya City of Copán, Honduras

The case study is the ancient Maya city of Copán. Today, Copán is a UNESCO World Heritage Site, but from the 5th to 9th centuries CE it was the center of a kingdom that at its peak covered about 250 square kilometers. Located at the southeast periphery of the ancient Maya world, it was an important cultural and commercial crossroad (Bell et al. 2004; Fash 2001). To begin to explore this question of "What roles did sound play in the urban dynamics of the ancient Maya?", we focus on the reign of Ruler 13, Uaxaclajuun Ub'aah K'awiil, who ruled the Copán kingdom from 695CE until he was decapitated by a nearby vassal state in 738CE.

Ruler 13 is known for introducing high-relief stelae and sculpture to the city. Scholars hypothesize that he commissioned the overhaul of Copán's Great Plaza, erecting several stelae within this open, public plaza to form a ritual circuit that he traversed in public performances (Newsome 2001). He also commissioned one of the city's most impressive temples, Temple 22, which he placed in the en-

closed, private space of the Acropolis (von Schwerin 2011).
Presumably, the differential placement of this architecture held significance and differentially shaped the experiences of ancient Maya people in the eighth century. But, what were these experiences, how did experience differ based on audience, and more specifically can we use acoustics to enrich our understanding of ancient Maya ritual performance and architectural design and ultimately its impact on urban dynamics?

Methods—
Computational and Experimental

To begin to address these questions, we have designed a two-prong methodological approach that is computational and experiential. The computational part uses GIS and 3D modelling to derive quantitative data for acoustical analysis. The experiential part employs immersive virtual reality to offer a sense of past experience that involves vision, sound, and bodily movement.

Computational

GIS for Sound Propagation Calculations | Spread-GIS is an open source ArcGIS toolbox (a series of five Python scripts) for modelling propagation of anthropogenic noise in wilderness settings (Reed et al. 2012). While the toolbox is primarily used for modelling the effects of noise pollution in ecosystems (Lorig 2016), a few archaeological applications exist. Researchers successfully applied Spread-GIS to calculate sound propagation in Levantine rock art sites in Spain (Díaz-Andreu and Mattioli 2015). In the U.S. Southwest, Primeau and Witt (2017) modified the scripts to create a new Soundshed Analysis tool, which they employed to model the propagation of sound at 33 sites within the Chacoan landscape (New Mexico). However, our approach differs from previous applications in two important ways: (1) we apply Spread-GIS in an urban landscape and (2) we incorporate 3D modelling data of architecture.

The ancient Maya are often viewed as practicing urban agrarianism (Isendahl and Smith 2013)—thus, to calculate noise propagation requires a modelling approach that incorporates both ecosystem and urban data, making a modified version of Spread-GIS appropriate. We made minor changes to the Python script to improve output resolution from 100m to 1m (to account for architectural features such as platforms, stairs, etc.), and adjust for syntax and other changes from ArcGIS 9.3 to ArcGIS 10.4.1.

Several environmental variables are required to run Spread-GIS. They include: temperature, humidity, wind speed, wind direction, and time of day. We use weather forecasts from Copán Ruinas, Honduras to fill these parameters, because they adequately represent past climatic conditions. Terrain (Digital Terrain Model-DTM) and land cover data (as raster) are also required. The MayaArch3D Project provided a 1m resolution Digital Terrain Model (bare earth) generated from airborne LiDAR (von Schwerin et al. 2016), but the analysis requires an Urban DEM comprising bare earth and archaeological structures. The MayaCityBuilder Project provided a 1m resolution Urban DEM (Richards-Rissetto 2017a) representing Copán's archaeological surface during the reign of its final dynastic ruler, Ruler 16, circa 800CE. However, our analysis requires an Urban DEM from the reign of Ruler 13, approximately 50 years earlier circa 750CE. To create this second Urban DEM, we modified the heights of structures from Copán's main civic-ceremonial complex—removing structures that did not exist (e.g., 10L-18, 10L-22A) and reducing heights of other buildings that existed but were not as tall (e.g., 10L-11, 10L-16)(Figure 2). We generated land cover data by combining geological, hydrological, and ecological data into vector data (shapefile) and converting to raster data with the attributes required to run Spread-GIS (Baudez et al. 1983; Fash and Long 1983).

Sound is produced when an object or substance vibrates and energy is transferred in a wave that alternatively expands and contracts, a cycle that repeats until the energy of the wave has dispersed (Moore 2005). This sound energy is measured by pressure and frequency using decibels and hertz. Decibels measure sound pressure (volume) and hertz measure sound frequency (pitch), or how many times per second the energy wave goes up and down. Objects with less air pressure have lower volume, and objects with a lower hertz (low-pitched sounds) have waves that go up and down slower and take longer to dissipate. The decibels and hertz of the sound source must also be set in Spread-GIS because, for example, drums

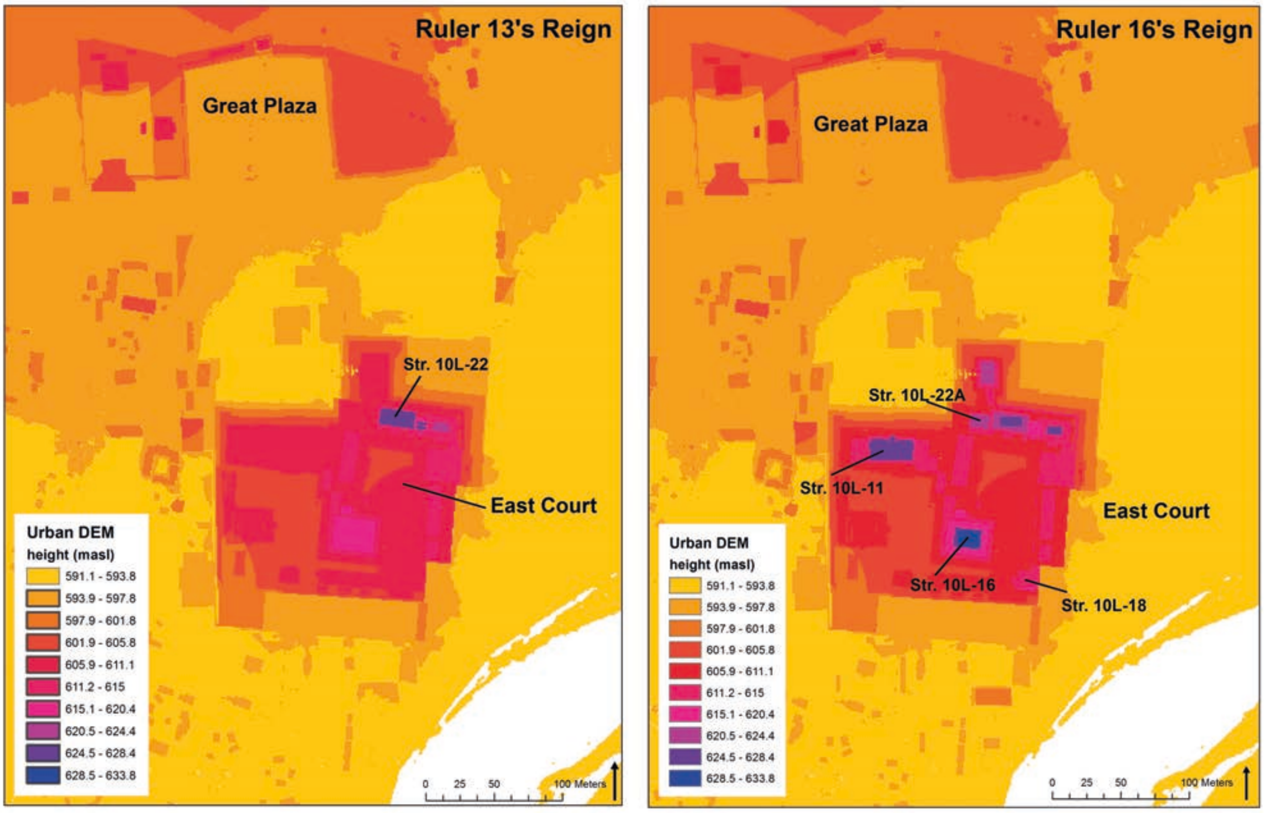

Figure 2. Urban DEM of Copán's main civic-ceremonial complex; East Court structures with heights for Ruler 13's reign; (left) East Court structures w/heights for Ruler 16's reign (right).

versus a human voice have different sound energy that affects sound propagation.

Spread-GIS has five modules—each module introduces a factor influencing sound propagation and requires data derived in a previous module. A shapefile (point) representing the location(s) of sound sources along with the Urban DEM and Land Cover data are required to run Module 1. Module 1: *spherical spreading loss*—the decline in sound level based on distance from the sound source. Module 2: *atmospheric absorption loss*—the decline in sound level due to air temperature, humidity, and elevation. Module 3: *foliage and ground cover loss*—the decline in sound level due to vegetation and terrain. Module 4: *downwind and upwind loss*— directional changes in sound level due to wind direction, speed, and seasonal conditions. Module 5: *terrain effects*—decline in sound level due to barrier effects from hills or ridge lines. The final output is a floating-point raster dataset that provides data on sound propagation in a landscape setting.

3D Modelling for Sound Reverberation Calculations | Trimble SketchUp is a user-friendly 3D modelling software that allows users to easily calculate surface area and volume—two measurements essential for calculating reverberation time and building capacity (i.e., number of potential occupants). The first step is to calculate reverberation time. Reverberation time is the time it takes for an echo to fade in a space. It is important for the clarity of speech and music. Too much reverberation and words become muddled, too little reverberation and a person's voice or music will not carry as far (McBride 2014). In ritual contexts, reverberations induce sensation among performers and observers (Hume 2007). Reverberation can aid in detection of otherwise inaudible sounds and help amplify sounds across space (Bruchez 2005). Architectural design directly impacts reverberation because sound is affected by the amount a surface reflects or absorbs sound and the dimension, shape, and properties of the space in which any given sound is produced (Mills 2014). The calculation requires three parameters: (1) surface area, (2) volume of a space, and (3) absorption coefficients of building materials (how much sound particular materials absorb). The equation is:

Reverberation Time (seconds) = Constant (0.049 for feet, 0.16 for meters)*Room Volume/Area Total [a]

[a] *Area Total = Surface Area x Absorption Coefficient*

Equation 1. Calculation for total reverberation time for architecture using 3D models.

For absorption coefficients, we used modern equivalents for stone and plaster to represent ancient building materials (McBride 2014). However, absorption coefficients do not remain constant; rather they vary by sound frequency, i.e., sound source. Furthermore, because sound is a wave of energy that oscillates, it is affected by the medium it passes through. Wind, temperature, background noise, reflection, refraction, and diffraction of sound all play a role in how far a sound travels. Hertz (or frequency) refers to how many times per second a sound wave moves up and down. A sound with a lower Hertz travels slower, dissipates slower, and tends to travel farther. Decibels (dB) measure the intensity of a sound. A sound with higher decibels is perceived as louder. Frequency of the human voice is typically between 80-500 Hertz (Hz). For this reason we chose to calculate frequency results for 125, 500, and 2000 Hz to cover the range of the human voice and also instruments. And, following Jerry Moore's (2005) we measure intensity using four categories: inaudible (0-10 dB), faint (10-40 dB), moderate (40-70 dB), and loud (70-100 dB) (Table 1).

The second step to calculate reverberation time is estimating the number of people that can fit in a space. The number of people affects reverberation time by increasing the number of potential sound sources, and surfaces for sound to reflect off. The relationship between acoustics and audience size is important because a tightly packed space can hold more people, but leaves less room for dynamic performances such as dancing or processions. Based on Takeshi Inomata's (2006) study of performance and capacity within Maya plazas, we test the impact of number of people on reverberation time for 0.46 m, 1.0 m, and 3.6 m per person.

Experiential

The main objective of the experiential component is to begin to move beyond simply a visual experience in VR. Knowledge of the world relies on senses, and localization of a person within their environment is enhanced by interactions between auditory and visual sensations (Bruchez 2005; King and Santiago 2011). Spatial audio simulates the spaciousness of sound creating more immersive VR experiences by better situating users within 3D environments. Data from the MayaArch3D and MayaCityBuilder projects are being employed to create a VR landscape for ancient Copán (late eighth century) within the gaming engine Unity3D (Day and Richards-Rissetto 2016). Using the Unity 3D platform and Dear-VR, a Unity plug in that simulates human spatial hearing via head-tracking in VR headsets—we make use of the Oculus Rift headset to explore the potential of a synesthetic experience to induce a greater sense of embodiment by combining vision, sound, and movement (Fernández-Palacios et al. 2017; Forte and Siliotti 1997).

Results

This section presents and compares the GIS sound propagation results for the open, public Great Plaza and the enclosed, private East Court to explore the potential role acoustics played during ritual performances. For the East Court, we also present the 3D

Subjective Experience	Modern Examples	Map Color and dB Level
Inaudible	10 dB Breathing	White (0-10 dB)
Faint	20 dB Whisper	Yellow (10-40 dB)
Moderate	50 dB Background conversation	Blue (40-70 dB)
Loud	90 dB Jackhammer	Pink (70-100 db)

Table 1. Intensity measures for acoustic analysis of subjective experience (based on Moore 2005).

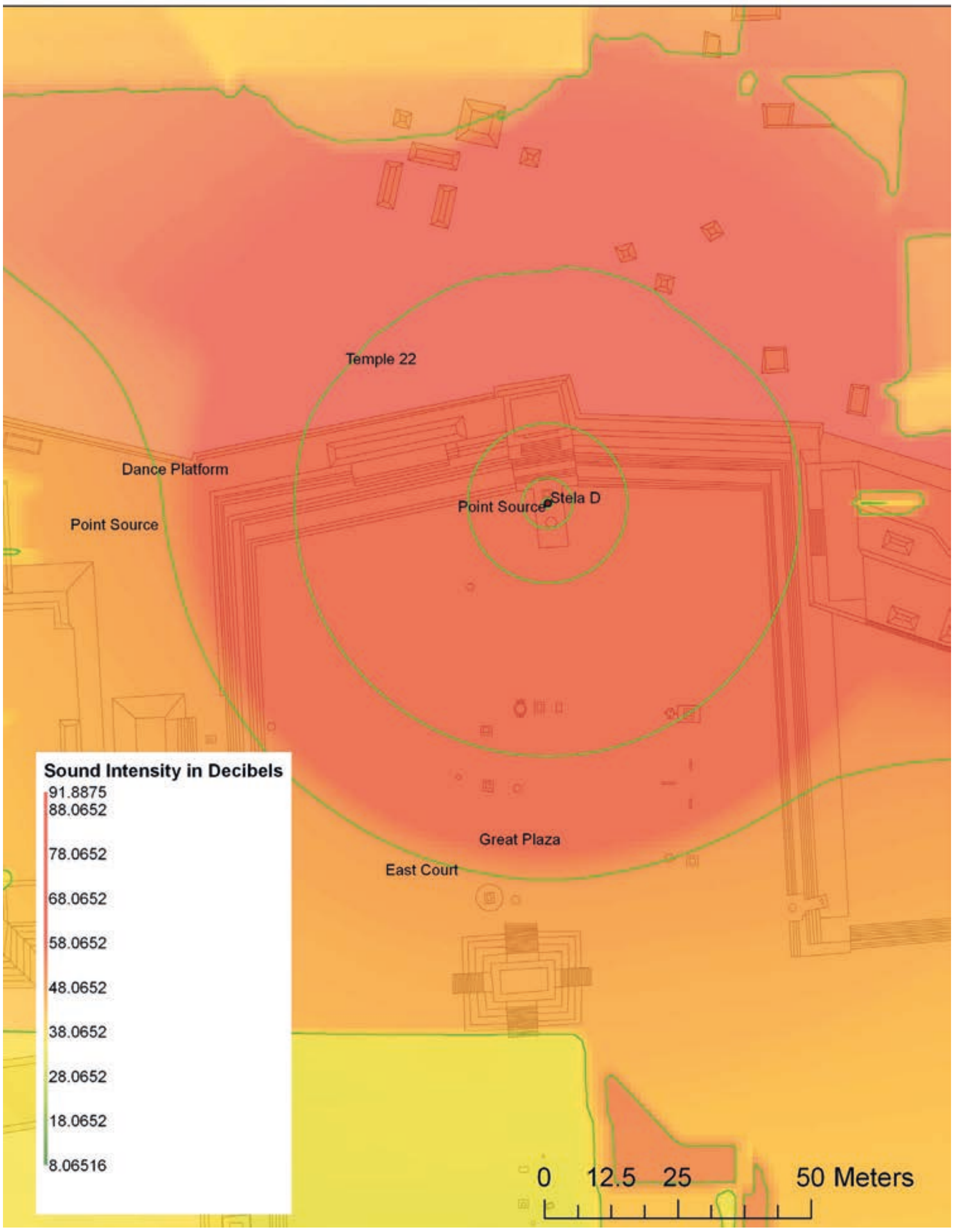

Figure 3. Sound propagation from Stela D, Great Plaza, Copán.

modelling reverberation results to further investigate the potential role of acoustics in ritual performance within "enclosed" spaces. Before continuing it is important to define what we mean by audible, and intelligible. We define audible as words being heard but not necessarily understood, while intelligible is defined as the words being understood. The parameters entered into Spread-GIS were:

Parameters of Sound Source:

- Frequency (Hz): 250
- Sound Level (dB): 75
- Measurement distance (ft): 50

Environmental Parameters:

- 79 Degrees Fahrenheit
- Humidity: 90%
- Average Wind Speed: 3 MPH
- Direction at 25
- Calm, Cloudy Day

GIS Propagation Results

Great Plaza | Current interpretations suggest that Ruler 13 began his ritual circuit atop Structure 10L-4—a stepped pyramid that served as a dance platform evidenced by dancing Maize God iconography,

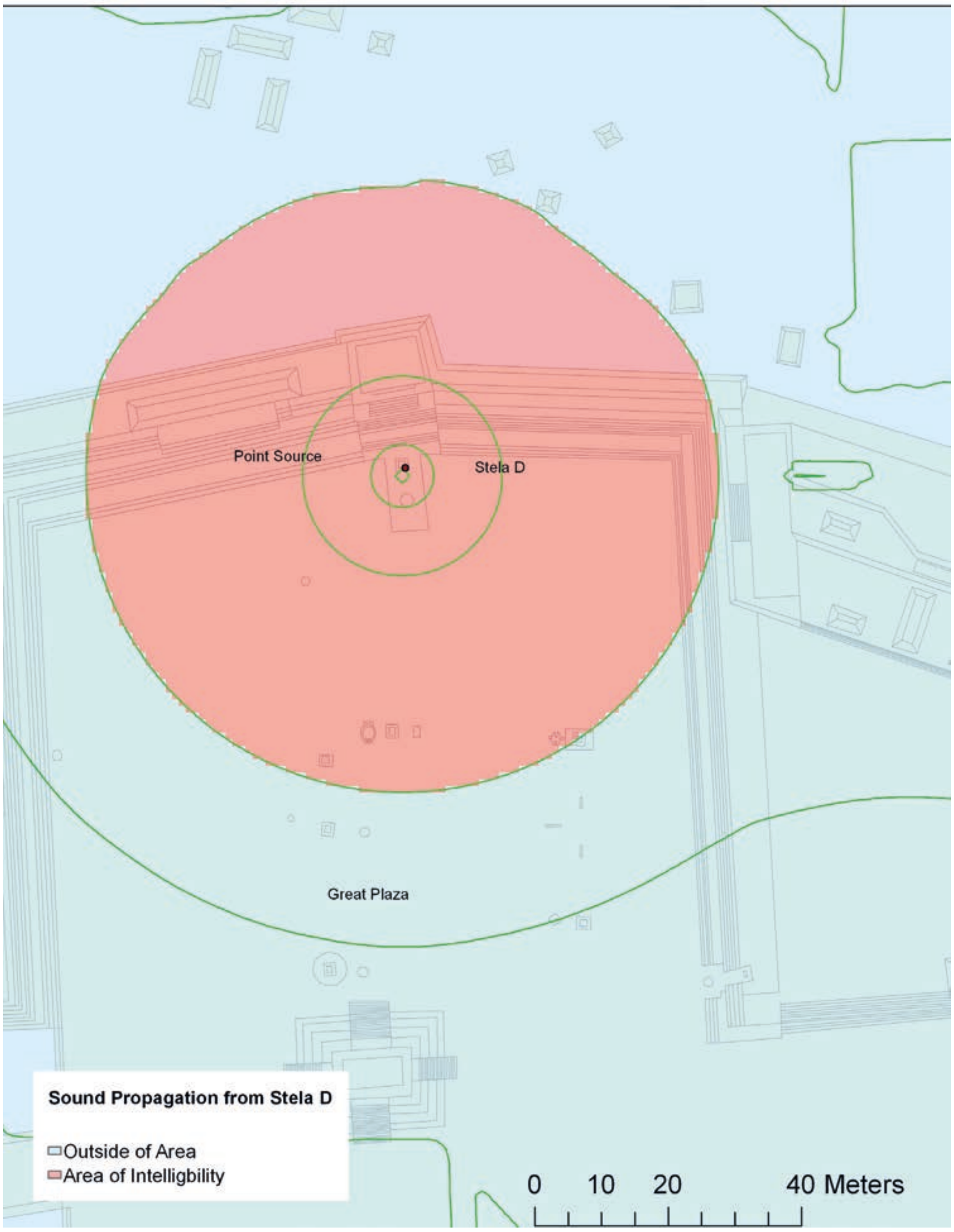

Figure 4. Map highlighting space in Great Plaza where speech would be intelligible from Stela D.

and proceeded down the step to process through the Great Plaza's seven stelae (Newsome 2001). We selected a source point placed at Stela D to represent a location where Ruler 13 might have stood during a ritual procession. Figure 3 shows a raster surface of sound propagation from Stela D. The results indicate that someone speaking at this location would be audible to people sitting on the steps surrounding the Great Plaza Stelae, supporting the hypothesis that these steps served as bleachers for an audience (Inomata 2006); but were the speaker's words intelligible, and if so, from what locations?

Figure 4 illustrates that area of intelligibility from Stela D (based on 60dB or higher). Table 2 compares total audience capacity to number of people able to hear and comprehend a speaker at Stela D. The results suggest that 0.46m per person is ideal spacing to maximize the number of people to directly hear a speaker's words in the Great Plaza; however, regardless of audience size approximately 9% of attendees could decipher a speaker's words. However, this does not mean that Stela D did not serve as an "oration" space for all participants. While the stela served as a visual focal point it would have also been an auditory attraction forming part of complex ritual performances that spoke to the Maya emphasis on synesthetic experience (Looper 2009). As humans we communicate beyond our voices; visual cues re-

Meters per person	Capacity (# people) Great Plaza	# of People Intelligible Speech	% audience (intelligible)
0.46m	27,711	2504	9%
1.0m	12,747	1152	9%
3.0m	3,541	384	9%
Loud	90 dB Jackhammer	Pink (70-100 db)	

Table 2. Comparison of audience capacity to persons able to hear and comprehend speaker from Stela D.

inforce spoken messages. Moreover, a comparison of visual to auditory results can provide information on audience members and their social standing within ancient Maya society—individuals seated within areas of intelligibility may reflect acoustical targeting.

East Court | We used the same sound and environmental parameters in Spread-GIS to investigate sound propagation from the steps of Temple 22 in the East Court (Figure 4). The Spread-GIS propagation results indicate that a speaker from the steps of Temple 22 could be heard throughout most of the East Court but would likely have to rely on a raised voice, instruments, or visual signals (such as a headdress) in order to send a desired message to the entirety of the East Court (Figure 5). The acoustic results support hypotheses that Temple 22, dedicated by Ruler 13 in 715CE, served as a focal point for performance and that the East Court was an exclusive performance space for the elite (Inomata 2006; von Schwerin 2004, 2011). However, because sound, albeit unintelligible, was able to also be heard outside the East Court, the results suggest that others (non-elite) were meant to hear the performance, yet simultaneously be excluded; similar to seeing the highly visible Temple 22 and yet not able to directly access it (Richards- Rissetto 2010, 2017a).

Figure 6 reveals further analysis of East Court acoustics. Propagation results from the elevated Jaguar Dance platform 10L-1 (Looper 2008) suggest that it was an effective platform for vocal performance in the East Court with a larger soundscape than the Temple 22 stairway. While only some audience members within the East Court could see a performance situated on 10L-1, all audience members in the East Court and many beyond could hear the performance. These results also reinforce differential access to ancient Maya performances—only a small percentage of Copán's inhabitants could see a performance in the East Court, yet many elite and non-elite could hear it. Together, vision and sound were complementary. For some within the East Court they offered a synesthetic experience, but for others their experience was limited to one sense, i.e. sound, creating differential experiences and sending different messages to "audience" members.

The results indicate that 1-2 seconds reverberation time is ideal for clarity of speech and music; in contrast, at 3-4 seconds there is loss of articulation and difficulty understanding speech (Nave 2017). When the number of people in the East Court is between 0.46 and 1.0 meters per person, sounds at 500Hz, or 2000Hz have reverberation times between 1.287 and 2.54 seconds. It is reasonable to suggest Maya rulers would desire vocal clarity when addressing large crowds and Maya musicians would desire instrumental clarity when performing; thus, the results indicate that an audience size between 4,435-9,641 persons (based on Inomata 2006) is ideal for ritual performances involving speech as well as musical instruments in the East Court.

3D Modelling Reverberation

To further understand the acoustics of the East Court and its potential role in ritual performance, we calculated reverberation time from the East Court. Surface area, construction materials, and number of people in a space affect reverberation time; we used previously estimated capacities for the East Court (Inomata 2006). Figure 7 shows the 3D model in SketchUp used to calculate reverberation times using Equation 1 and Table 3 lists calculated reverberation times of the East Court.

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# of People	Meters per person	Reverberation Time (secs)—125Hz	Reverberation Time (secs)— 500 Hz	Reverberation Time (secs)—2000Hz
# of People	person	125Hz	500Hz	2000Hz
9,641	0.46m	Apr-97	Jan-37	1.287
4,435	1.0m	Aug-42	Feb-54	Feb-17
1,232	3.0m	Nov-23	Apr-75	Mar-84
Empty	N/A	Dec-51	Jul-51	May-48

Table 3. Reverberation time in the East Court for a sound at 125Hz, 500Hz, and 2000Hz.

500Hz, or 2000Hz have reverberation times between 1.287 and 2.54 seconds. It is reasonable to suggest Maya rulers would desire vocal clarity when addressing large crowds and Maya musicians would desire instrumental clarity when performing; thus, the results indicate that an audience size between 4,435-9,641 persons (based on Inomata 2006) is ideal for ritual performances involving speech as well as musical instruments in the East Court.

Conclusions

Archaeologists increasingly use GIS and 3D modelling to examine vision and movement within landscapes; however, few researchers have investigated the potential role of sound across ancient landscapes. Using a case study from the ancient Maya city of Copán, we have employed Spread-GIS, 3D modelling, and VR to begin to explore the role of acoustics in ritual performance and differential audience experience.

Proxemics, a term coined by Edwin Hall (1969) referring to how people use space in communication, categorizes interactions into four separate spatial distances: intimate, personal, social, and public. Researchers hypothesize that the open Great Plaza at Copán served as a performance space for large audiences comprising both elite and non-elite attendees. While the GIS results support this interpretation indicating that a speaker could be heard throughout the Great Plaza, the integration of GIS and 3D modelling provides additional information of differential audience experience. Initial calculations show that regardless of audience size, only about 9% of attendees could actually decipher the words of a speaker at Stela D, a hypothesized performance location along a ritual circuit in the Great Plaza (Newsome 2001). However, the placement of the Great Plaza's seven stelae suggests that movement combined with sound was integral to performance. Six of the seven stelae are located within 14 to 42 meters of the "bleachers"—this public spatial distance (far phase) is ideal for communicating with a large group; only Stela C is not within this public distance. Thus, as a performer (presumably Ruler 13) processed through the Great Plaza, the majority of audience members would be "incorporated" within the ceremony. Future work will compare soundsheds to viewsheds to determine if overlap and/or complementarity exist between vision and sound at each of the Great Plaza's stelae.

As for the restricted and enclosed East Court, researchers contend it was an exclusive performance space for the elite with Temple 22 and Structure 10L-1 serving as focal points for performance (Inomata 2006; von Schwerin 2004). The distance from the top of the Temple 22 stairs to the plaza floor below is 5.5 meters. In proxemics this distance fits within the public distance, close phase (3.6-7.6 meters) suggesting someone speaking from the stairs would be at an ideal distance for addressing a group gathered at the base of the steps; however, the enclosed courtyard comprising stairs (possibly serving as bleachers) allows a voice to reverberate across the space extending the impact of a speaker's voice. 3D modelling results reveal that when audience spacing is between 0.46 and 1.0 meters per person sound propagation is ideal.

However, performances atop the Jaguar Platform (Str. 10L-1) on the west side of the East Court could address larger audiences via sound propagation and reverberation. Based on population estimates, approximately 5-10% of Copán's population could participate in a ritual event held in the East Court supporting interpretations of it as a performance space for the elite. And yet, interestingly, the GIS sound propagation results indicate that people outside of the East Court could hear voices and instruments suggesting that these secluded events, while visually restricted, were still meant to be heard. The fact that they could be heard but not seen would have created an air of mystic enhancing elite power.

Theatrical events and politics are closely linked in Classic Maya Society, and dynastic rulers benefited from the creation of memory through public ritual (Inomata 2006). While physical distance is a major factor in the regulation of human interaction and experience, urban design and elements of the built environment also influence social experiences. The placement of temples, plazas, freestanding monuments, stairs, and other built forms regulate interaction by insulating some individuals for small, private affairs and welcoming large crowds for other large, public events (Moore 2005). Among the ancient Maya, synesthetic experiences incorporating multiple senses were integral to daily life and ritual performance (Houston et al. 2006). The spatial organization of cityscapes differentially affected human experiences—they were not the same for everyone. Large, open spaces accommodated more people, inviting them to participate in events through sight and sound. In contrast, small, enclosed spaces restricted audience size allowing only a relative few to see a performance and yet through sound others, outside of the performance space, could still participate—simultaneously sending messages of inclusion and exclusion to Copán's non-elite inhabitants; thus, promoting social cohesion alongside messages of elite power and authority.

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The Metrological Research of Machu Picchu Settlement: Application of a Cosine Quantogram Method for 3D Laser Data

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Abstract

The purpose of this research is to look for a basic unit or units of measure (quantum), the multiplication of which would help delineate the outline of Inca settlements such as Machu Picchu. By making use of the statistical method developed by D. G. Kendall, the cosine quantogram, and dealing with data acquired through 3D laser scanning, we can answer the question about Inca imperial measurement system. Based on length measurements from the construction level of niches, we can conclude that an imperial system of measure existed. Three basic units of design were used in different ranks and functions of the building, as follows: 0.20 m; 0.41 m; 0.54 m.

Keywords: Inca architecture, length measurement, statistics, metrology, 3D laser scanning

Introduction

The Inca Empire formed a conglomerate of many ethnic groups and languages. The Inca elite formed a small community of around 300,000 - 500,000 people out of the 6 to 14 million people in the empire (Szemiński and Ziółkowski 2014:34-35). In terms of territorial extent in the middle of 15th century, the Inca state covered an area encompassing parts of the of modern nations of Columbia, Ecuador, Peru, Bolivia, Argentina, and Chile. The life of the empire's inhabitants was controlled on many levels by the Inca administrative authorities who managed the labour service for the state (*mit'a*). The Inca urban planning and architecture was characterized by the standardization of forms, structures, and function; however, there was a great deal of variability due to local traditions.

The aim of this research is to verify the hypothesis about the presense of a basic unit (quantum) of length measurement used by the Inca to delineate the architectural complex of Machu Picchu. This paper is focused on the methodological part of the research based on the cosine quantogram method, Monte Carlo verification, and hypothesis testing of equal quanta (basic units of measure) between buildings. We have made use of already known algorithms and statistical techniques. Our own implementation has been developed using the free, open-source software environment R (Kasiński 2019)[1].

The subject of research, Machu Picchu, was an imperial investment of Inca Pachacuti (Rowe 1990:141-145). The general layout of Machu Picchu seems not to have been achieved by chance but rather deliberately planned. It is visible in the spatial organization of the architectural complexes where each sector has a specific border carefully arranged on *andenes* (terraces). Engineering skills visible in wall construction and stonework suggest that a building layout plan must have existed. Inca architects/engineers and stonemasons supervised imperial constructions, but the scale of their influence in the construction process of the settlement plans is unknown because there is no information in Colonial documents. The process of building construction mainly relied on the great workforce of temporally working people (*mi-*

1 The creation of R package would not be possible without R software environment authors (R Core Team 2016; Wand 2015; Wickham et al. 2018; Wickham and Henry 2018), as well as authors of useful R graphical helpers (Hocking 2017; Neuwirth 2014; Wickham 2016).

Measure	María Rostworowski de Diez Canseco [cm]	Wendell C. Bennett [cm]	John Rowland Rowe [cm]	Santiago Agurto Calvo[cm]
sikya	81.0	81.0	84.0	80.0-84.0
cuchuch	_	45.0	45.0	40.0-45.0
chaqui	21.0	20.0	25.0	25.0-30.0
yuku	10.0-12.0	10.0-12.0	10.0-12.0	10.0-15.0

Table 1. Small measurements comparison based on modern scholars' studies of Quechua dictionaries.

tayoq), who were gathered from different parts of the Inca realm to provide a labour tax for the Inca state (Rowe 1946:69). The Inca Empire was composed of dozens if not hundreds of different ethnic and tribal groups (Rowe 1946:185-192), many with distinct languages and maybe with a different tradition of length measurement. There is no information from written sources about work duration or the number of people working and living in Machu Picchu. However, bioarchaeological and skeletal studies of the individuals buried at Machu Picchu (shows the ethnic diversity of the site's population where the skeletons of commoners include natives of both the coast and highlands (Turner and Hewitt 2018; Turner et al. 2009; Verano 2003).

Our knowledge about Inca measurement is based on information from post-conquest chronicles (Betanzos 2004 [1576]:88,98,116) and modern studies (Table 1) of 16th century Quechua dictionaries of Padre Gonzales Holguin or Fray Domingo de Santo Tomas. Based on that we can presume that Inca used an anthropometric system of measurement where the basic unit was adopted from body parts, like fingers (Quechua: *yuku* – distance from the tip of outstretched thumb and forefinger), foot (Spanish: *pie*, Quechua: *chaqui*), or cubit (Spanish: *codo*, Quechua: *khococ*). Because of the lack of written sources or archaeological finds of measuring devices, a statistical approach to these studies is needed to test whether there was a standard system of Inca measurements reflected in the architecture of Inca imperial constructions like Machu Picchu.

Methodology

Machu Picchu in the 3D Point Cloud

For the purpose of digital documentation and these studies, the agricultural and urban zone of Machu Picchu were scanned with a Leica P40 terrestrial 3D laser scanner. Beginning in 2010, research and documentation[2] have covered the whole urban zone of Machu Picchu with more than 600 scanner positions. The 3D point cloud obtained from scans is the most accurate form of measurement for this type of site. The varied landscape and complicated geometry of trapezoidal Inca edifices require a detailed and high-resolution dataset with visible type and course of masonry. The dataset collected from the 3D point cloud was initially transformed into vectorised plans and sections. Each plan contains desired measurements that are collected in the textual database for quantum analysis.

Data Selection

Building plans have three levels of layout: a foundation, a level of niches or windows, and a top level of masonry walls to support a roof construction. These studies are concentrated on non-invasive techniques of documentation, so it is not possible to reach the foundation level or even to establish how deep an individual footing of the building is because of the irregular bedrock of the mountain. However, in the masonry courses of Inca walls, we can observe a horizontal level used for placing windows and niches. Whole building interiors are occupied with niches or windows arranged in a row in specific intervals. Trapezoidal in shape with the shortest side on the top, they are noticeable in all kinds of Inca buildings across the empire, not only in sacred places. Niches are usually situated approximately 120-150 cm above a floor level and their function can be different depending on their location and size (Protzen 1993:221). Based on the observation of the course of

2 Team from 3D Scanning and Modelling Laboratory (Wroclaw University of Science and Technology) and The National Archaeological Park of Machu Picchu.

Figure 1. The wall of Kallanka (Sector 5D) with construction phases, orthoimage.

stone blocks in the wall and construction of window's stone frame, Niles (1987) presented a theory that the walls were built up to the desired height of the sills for the niches, after which frames for the niches were constructed at the specific intervals. When all the frames were placed, the gap between them was filled and additional courses of masonry (Figure 1). Length dimensions of niches and width and intervals between them were included in the dataset due to their uniformity in building plans. These measurements are significantly small, in terms of value, as well as large in terms of sample size to conduct the cosine quantogram statistic test. Their role in building layout and construction features potentially suggest the existence of standardized measurements in Inca building plans.

Data Characterisation

We divided the urbanized site of Machu Picchu into separate architectural sectors based on the modern subdivision of the site and common architectural and masonry features (Figure 2). Length measurements [cm] on the level of niches were assigned to each wall of a building. Groups of buildings having the same function, layout plan, and masonry were usually placed on the same terrace or two. This type of grouping was categorised as a sector within the established dataset. First, quantum searched the measurements of each building of the sector. By employing this step, we could exclude a possibility of more than two quanta per dataset, which would cause a distortion in the quanta score and eventually lead to an incorrect interpretation (Mustonen 2012). In most results for each building, there was only one candidate for quantum and for these cases the quantum estimation was calculated for the whole group, but when the results were divided, subgroups for sectors were established.

Data selection is probably one of the main questions behind ancient metrology. Which building elements can be used in the study of metrological units and how did the past builders of Machu Pichu follow the process of measurement execution? In regard to the niches, the question about the horizontal construction process emerged. We examined whether the corner measurements influenced the quantum estimation, but there also arose the question about the starting point of delineation. To find a solution for this question, we constructed five models. The first model excludes extreme left measurements, the second one excludes extreme right measurements. The third excludes both extremes, while in the fourth model all measurements are counted. The fifth, and final, model includes axes measurements (Figure 3). The differences of quantum values do not promote any of the five models but do exclude delineation between axes. Estimation of quantum does not significantly change after exclusion of corner measurements, probably because of the small ratio of corner measurements to interior measurements, which proves that the quantum in the series of measurements from widths and distance between niches exists.

Method Description

The cosine quantogram method used in this study was developed by David George Kendall (1974) for detecting a quantum of an unknown size from a set of data. A statistical model of cosine quantogram has been successfully implemented during the analysis of Mediterranean architectural sites as well as of

Figure 2. The plan of Machu Picchu, the urban zone with sectors marked, based on: Plano sub sectores llaqta Machupicchu (archives of Parque Arqueológico Nacional de Machupicchu).

European medieval urbanism (Cox 2006; Pakkanen 2001; Pakkanen 2004; Pakkanen 2005). In a case of Inca architecture, each building dimension of Machu Picchu can be described as an integer M multiplied by the basic unit q plus an error ε, i.e.

$$X_i = M_i q + \varepsilon_i$$

(Equation 1)

The error might be a result of ancient building execution as well as the modern method of measurement. In the equation ε, which is significantly smaller than q, is analysed and then the formula calculates an amount which clusters around q. Assuming a range of possible quantum values, cosine quantogram is defined as:

$$f(q) = \sqrt{\frac{2}{N}} \sum_{i=1}^{N} \cos\left(\frac{2\pi X_i}{q}\right)$$

(Equation 2)

Where N is the sample size and $\{X_i\}$ is the set of building dimensions. Applying (Equation 1) to (Equation 2) reduces the integer M and makes the formula depend directly on ε - the remainder of dividing a measurement by q. The value of q that maximizes the formula within a given range is the one with the highest probability of being a quantum. The term √(2/N) adds dependence of the cosine quantogram result on sample size. Unrounding the measurements, also proposed by Kendall (1974), makes the data a bit less sensitive to measurement

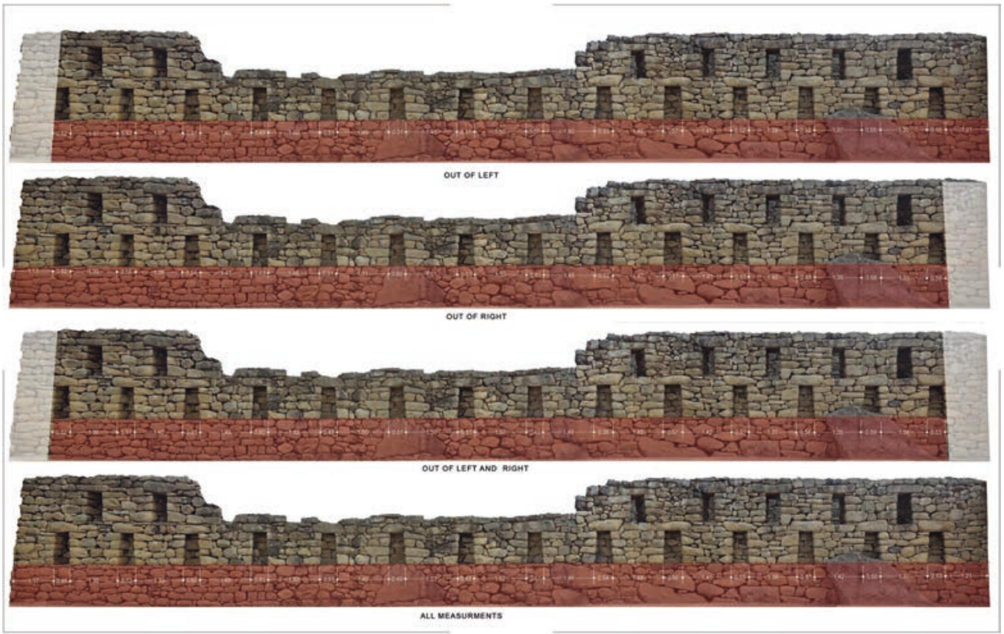

Figure 3. The four models of niches layout execution.

errors of any type. Unrounding is defined as adding a little random noise to each measurement. If measurements are rounded up to the nearest centimeter, a random number from a uniform distribution on the [-0.5cm, 0.5cm] interval is added. We apply unrounding to both original and sampled data before inputting it to the cosine quantogram.

Monte Carlo Validation of Quantum — Bootstrap Confidence Intervals

After applying the cosine quantogram to the niches data, we wanted to make sure the estimated quantum is neither evaluated by chance nor dominated by some outlier measurements. The Monte Carlo bootstrap method is used to construct confidence intervals – its limits determine the range of most possible quantum values. From the original data, a sufficiently large number of equal size samples are drawn with replacement. By "sufficiently" we mean the number of draws such that increasing it does not enhance the confidence of estimation. In our case the empirically determined number of draws is 1000. We tested that rate of convergence to confidence interval limits which is very low after that number. For each sample, after unrounding, the same cosine quantogram procedure is applied. This way we get a bootstrap distribution of the quantum parameter. Assuming 5% significance level, if quantum estimations for the original data fall within the confidence interval, it can be interpreted that the chance of the quantum happening by chance is very low. Specifically, in cosine quantogram problems, parameter distributions might be concentrated around few quanta, which requires a cautious interpretation of confidence intervals (Figure 4).

Quanta Equality Validation with Significance Tests

Evaluation and further verification of cosine quantogram results give rise to the question of whether little differences between estimated quanta lead to a single quantum. At this stage, two similar tasks are defined: first is to statistically verify that quanta in selected sectors are equal; the second is to verify that quanta in buildings within a given sector are equal. For this reason, we construct tests based on the maximum likelihood estimation.

Considering buildings within a given sector, the null hypothesis states that there is no significant difference between quantum for the entire sector and quantum for each building. The alternative hypothesis states that in at least one building, the quantum is different than the general one. In an analogous way, quanta equality is tested between sectors. Assuming data follows a von Mises distribution, we define the likelihood ratio function, which expresses how many times the original data under the null hypothesis model is more likely than under the alternative hypothesis. Without loss of generality, a logarithm of the LR ratio is taken as the test statistic. We construct a distribution of test statistics by employing Monte Carlo methods based on the KDE (kernel density

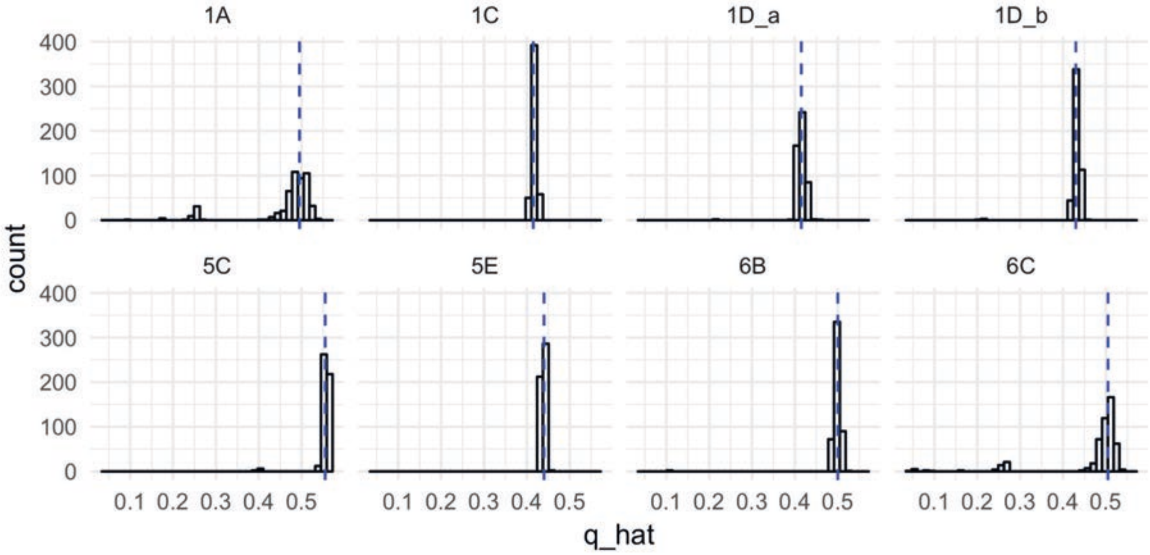

Figure 4. Bootstrap distribution of quantum parameter.

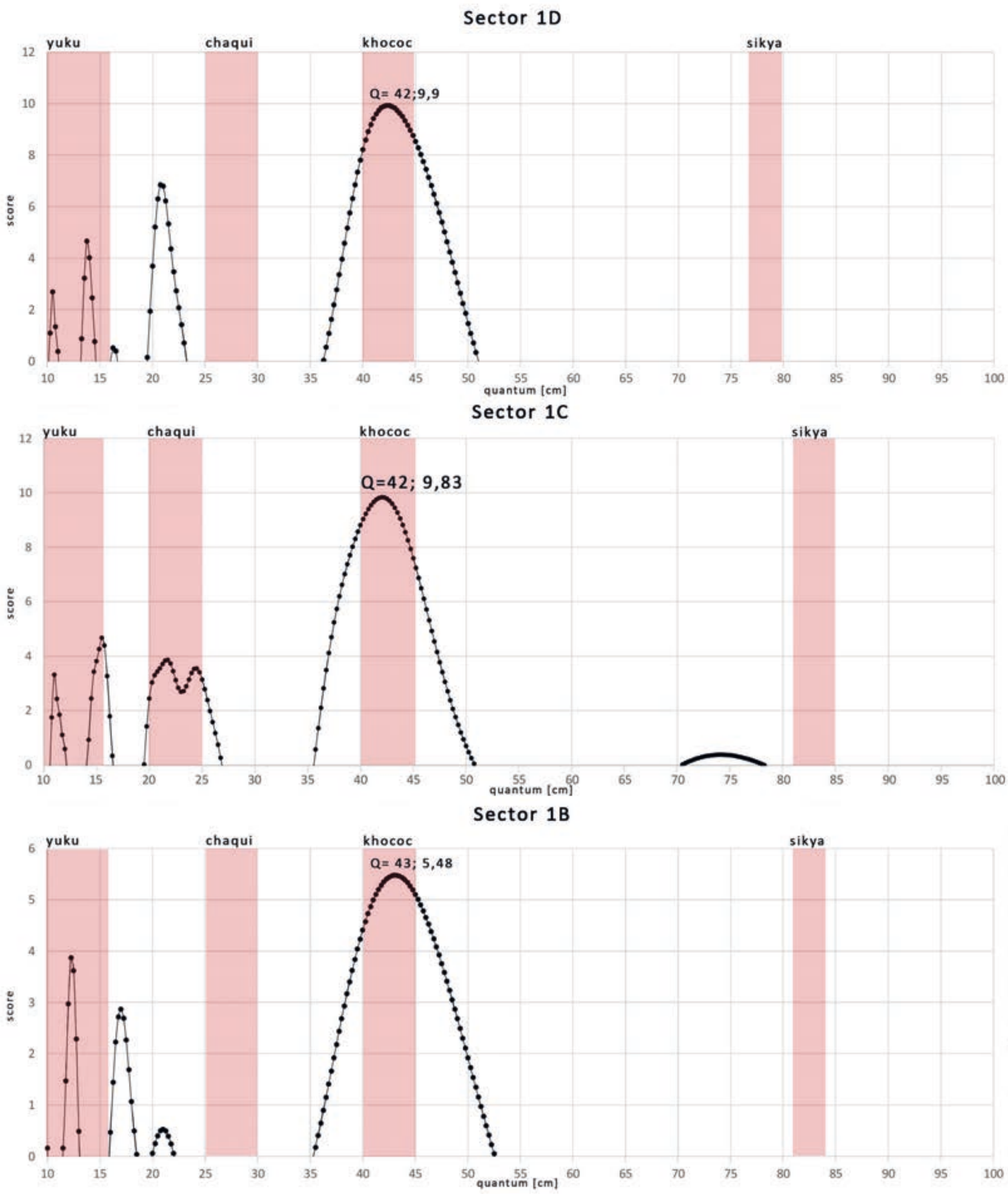

Figure 5. Quantum results for sectors: 1D, 1C, 1B.

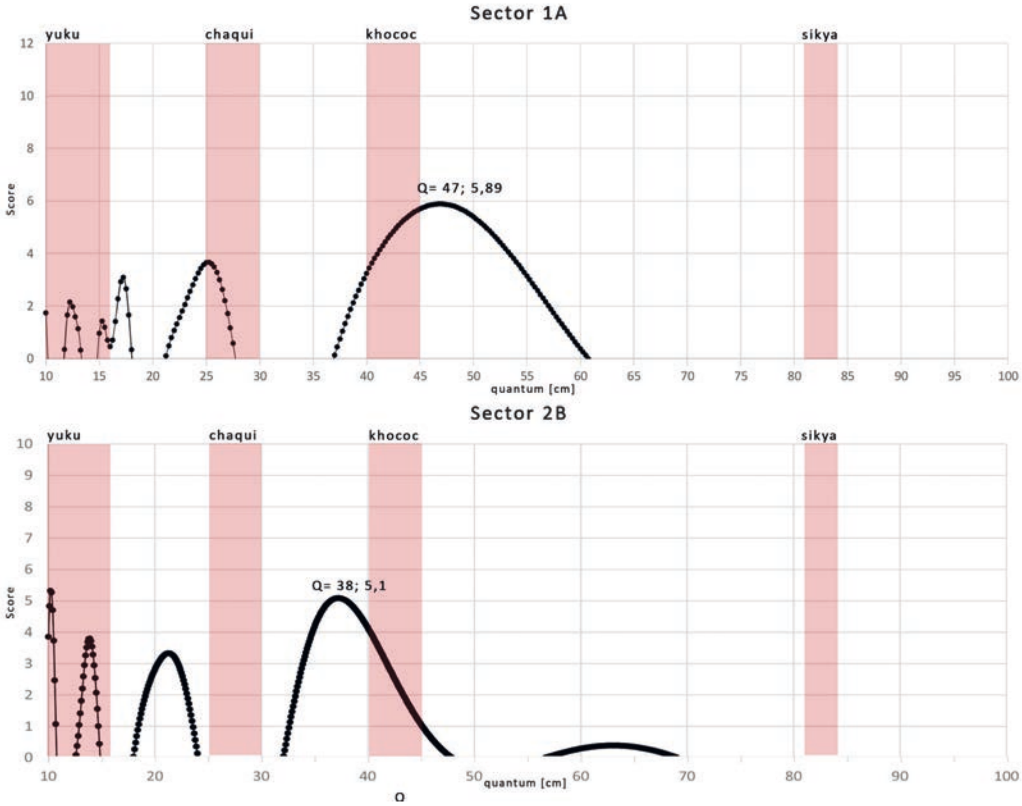

Figure 6. Quantum results for sectors: 1A, 2B.

estimator) model of data. In this approach, different than bootstrapping, samples are drawn from the theoretical distribution of measurements given by density estimation.

If the test statistic from the original data falls outside of the defined confidence interval, then the null hypothesis is rejected in favour of an alternative, which would support the idea that quanta are significantly different. Otherwise, accepting the null hypothesis means that there is a strong ground for quanta equality, but that does not provide us with the ability to ultimately prove it.

Looking for Quantum—Results

The range of dimensions collected from the level of niches is between 25 cm and 150 cm. In order to exclude meaningless quanta, lower and upper bounds of 10 cm and 100 cm were assumed. If smaller units were employed in building design and execution, it is doubtful that they could be discovered in a metrological analysis of rather large building dimensions included in this study.

Quantum results were obtained from a part of the urban area of Machu Picchu. Further research was conducted to test each building and sector at the site. The basic units of design were investigated on the west side of the main plaza (Sector: 1Da, 1Db, 1C, 1B, 1A, 2B) and the east side of the main plaza (Sector: 6B, 6C, 5C, 5E) (Figure 2). The results cover the region from the entrance of the site to the urban zone, which is dominated by buildings with a residential function. This part of the site consists of five modern sectors. Two of them: 1A ("*Casa real*") and 1B ("*Templo del Sol*") have masonry distinguished from the rest of the sectors which consist of the housing zone. Sector 1B is also different in terms of function, with two buildings of cut and fitted masonry, designed as the sacred Temple of the Sun. However, obtained quantum values in the most part (except Sector 1A) of the west side of the main plaza are estimated between 38 - 43 cm (Figures 5 and 6). Considering each sector separately, small differences could occur as a result of ancient measuring execution but planned quantum could be the same for whole architectural groups. Evaluation of this problem was statistically tested for equality of quanta in Sectors 1Da, 1Db, 1C, 1B. Results reveal that the hypothesis about quanta equality is accepted (Figure 7). The possible value range of quantum corresponds with a measure of a cubit (Quechua: *khococ*), which,

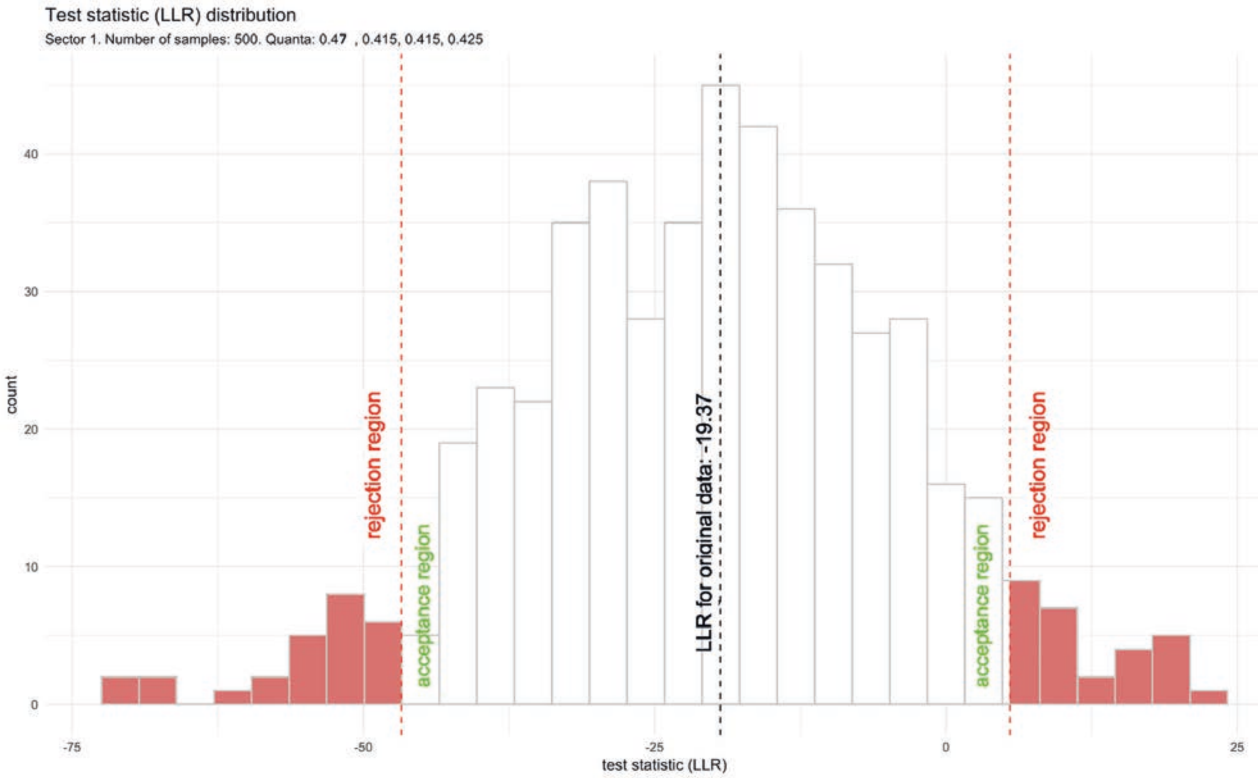

Figure 7. Test statistic (LLR) for equal quantum in sectors on the west side of the main plaza.

based on previous measurement studies, is between 40-45 cm (Rostworowski 1960:10-11). Multiplication of this measurement as a basic unit creates a whole system of length measurements: *sikya* = 81 cm (2*40.5 cm) and *rikra* = 162 cm (4*40.5 cm), which are known from the urban division of Ollantaytambo (Farrington 2013:70-76). While the Inca system of measurements as well as studies of Inca engineering (Wright et al. 2011:14-21; Wright et al. 2016:35-37) and building layout (Lee 1996) have been explored by scholars, they have never been based on metrological studies in the building scale.

The east side of the main plaza consists of high-status households organized in the form of *kancha* – the classic Inca household that contains rectangular units surrounded by an enclosure (Sectors 5C, 6B, 6C, 1A-from the west part). But *kancha* are not the only structures to occur on this side of the plaza. Behind each *kancha* is a type of small, domestic building that is grouped in a row without a courtyard. In Inca times they could have been occupied by servants (Quechua: *yanakuna*) dedicated to each elite compound (Salazar 2004:29-30). Differences between these domestic sectors are also visible in quanta results. For Sectors 5C, 6B, 6C, and 1A, the quantum is in the range of 47-55 cm (3*54 cm = *rikra*) (Figure 8), but in the eight small domestic buildings in Sector 5B and 5D, the value of the quantum is 20 cm (8*20 = *rikra*), which correspond to the size of a hand (k'apa).

WEST SIDE OF PLAZA	QUANTUM ESTIMATION [cm]	EAST SIDE OF PLAZA	QUANTUM ESTIMATION [cm]
1A	47	5B	58
1B	43	5C	55
1C	42	5E	45
1D	42	6B	50
2B	38	6D	44
		6C	50

Table 2. Quantum estimation for two sides of the main plaza.

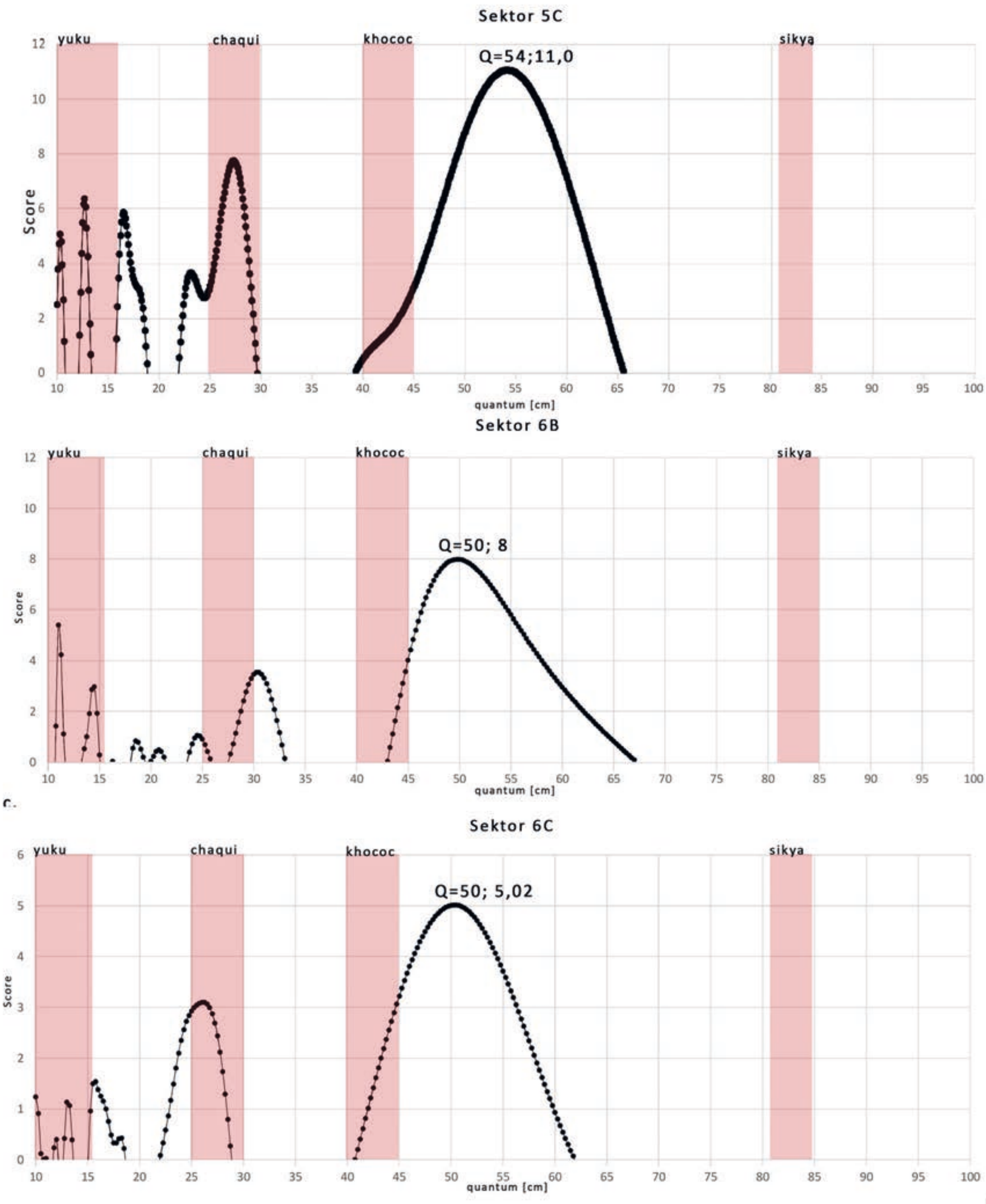

Figure 8. Quantum results for sectors: 5C, 6B, 6C.

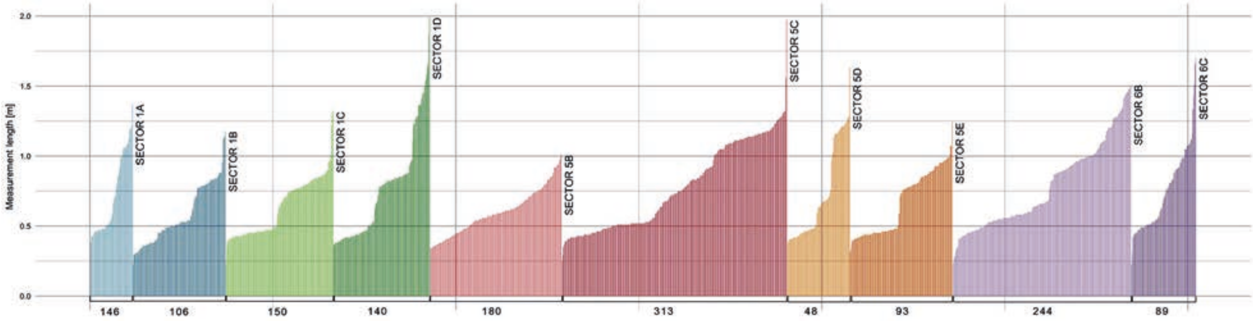

Figure 9. Distribution of length measurements on the level of niches for each sector.

Quantum results from sectors on the west side of the plaza were statistically tested for being equal because of the small differences between quanta within architectural groups. The Inca buildings on Machu Picchu were constructed of semi-cut or unworked fieldstones laid up in an argillaceous mortar. Based on the results we conclude that in this type of masonry it is not possible to distinguish one single unit of measurement. This means that quantum of 40 cm and the quantum of 44 cm are statistically indistinguishable. Apparently, inequality could emerge from ancient measuring execution, but not from the different local traditions of measure. A distinctive characteristic of housing design at Machu Picchu with simple, small houses on the west and elite housing compounds on the east was also evidenced in two different quanta, but in both cases, they are an integer multiple of a fathom (Quechua: *rikra*) 4*41, 3*54, 8*20.

The statistical approach in this metrological analysis revealed that based on length measurements from the construction level of niches we can conclude that an imperial system of measure for the Inca state could exist. Three basic units of design were used in buildings that had different functions and were associated with people of different ranks. These are as follows: 20 cm; 41 cm; 54 cm (Table 2). Further multiplication of these values coincides with other known length measurements from Hispanic sources: 81 cm (*sikya*), 162 cm (*rikra*). The non-invasive technique of documentation does not allow us to measure the layout of the building on foundation level; however, further studies are focused on the theoretical reconstruction of the base level in order to find measurements that correspond with a multiplication of the basic unit of design found in upper parts of Inca buildings.

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Mobile GIS in Archaeology: Current Possibilities, Future Needs. Position Paper

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Abstract

Ever since field survey has become an important method in researching ancient communities we can observe improvement of its technological and theoretical aspects. Nowadays, rapid urban sprawl and intensified agriculture lead to the increasing destruction of sites and archaeological landscapes throughout the globe. Thus, an adequate low budget strategies is needed, that will able help to document, preserve, study and manage all what is left. The introduction of GIS and GNSS mobile applications opened a such possibility. At the 2017 CAA meetings in Atlanta, the authors organized a session entitled "Mobile GIS in archaeology – current possibilities, future needs", at which the current issues and possibilities were discussed. The session resulted in this summary paper. The main aim of the paper is to re-evaluate the contemporary concept of the survey that was introduced due to a rapid increase of GPS accuracy and development of mobile technology.

Keywords: mobile GIS, archaeological field survey, surface archaeology, GNSS.

Introduction

Ever since field survey became an important method in researching ancient communities (Adams 1965; Ford and Willey 1949; Wedel 1953), the methodology has been adapted based on the constant increase of theoretical and technical aspects of the discipline. Surveys were gradually augmented with technological innovations (Wilkinson 2003: 33–40). Nowadays, field survey is relying on remote sensing and constantly developing GNSS systems. During the CAA conference held in Atlanta, USA in 2017, the authors had the opportunity to lead the session, during which new technological innovations and problems of the field survey were discussed. The session was titled "Mobile GIS and field survey - current possibilities, future needs".

During the session, six papers were presented. Each paper discussed case studies followed by a discussion about current possibilities of implementing mobile GIS. The first paper was presented by Peter Knoop and was titled "Best practices for mobile GIS and information technology in the field". The author presented different case studies of mobile GIS applications used on tablets and emphasized technical details that one must be aware of and problems that might occur during the survey. The second paper was presented by Austin Hill entitled "High accuracy drone survey methods". The paper discussed possibilities of using photogrammetric models created from UAV photos, and the possibility of using mobile GIS in this process.

The third paper was presented by Julia M. Chyla, Miłosz Giersz, Wiesław Więckowski, Patrycja Prządka-Giersz and Roberto Pimentel Nita, titled "One step further beyond field survey". The paper discussed the use of mobile GIS applications on PDAs in a regional survey of Huarmey Valley in Peru, and the methodological challenges of creating similar surveys. The fourth paper was presented by Łukasz Miszk, Wojciech Ostrowski, Weronika Winiarska, and was titled "Urban sprawl vs. archaeological site:

a view from Paphos". The presentation focused on the uses of GIS in the site management of Paphos on Cyprus. The paper emphasized the influence of the urban landscape on the preservation of the heritage in the region, which was one of the topics of the session. The fifth paper was presented by Hannah Pethen and was titled "Accessing the inaccessible: detailed 'offsite' archaeological survey using satellite imagery and GIS at the Hatnub travertine quarries, Egypt". The presentation focused on the preparation of field prospection in Egypt preceded by analysis of satellite images and the results of archival research. The paper emphasized the need of having efficient way to verify large amount of sites located with use of remote sensing. The last paper was presented by Nazarij Buławka and was titled: "Ancient landscapes and present-day agriculture – on the example of Tejen River (Turkmenistan)". The presentation discussed the efficacy of mobile GIS applications during field prospection at the Serakhs oasis in Turkmenistan. It focused on methodology from the perspective of mapping sites in the region. The ground truth of the collected data on site extent was discussed as well.

The session finished with a discussion about the future development of mobile GIS: why its application is needed in archaeological research, and what functions researchers hope that those tools might have in the future. During the session and the discussion, participants pointed out that the emergence of Mobile GIS is closely linked with developments in navigation technology (GNSS). The discussion prompted the writing of this position paper, in order to present the current state of knowledge about GNSS technology and the use of mobile GIS applications in archaeological research.

The aim of the paper is to re-evaluate the development of the surface surveys caused by the increase of GPS accuracy and practices of crowd collection. Mobile GIS is becoming increasingly popular in large-scale, field archaeological prospection nowadays. Thus, it is important to step back and see what this technology brought to archaeology. We have not encountered such reflexion in other papers that would sufficiently show the parallel changes within GNSS and field survey. Available articles describe only the rapid development of the technology and admire new possibilities for archaeology (Joglekar and Sushama 2008). The scholars also do not put contemporary Mobile GIS tools in the context of other GNSS techniques (i.e., Tripcevich and Wernke 2010; Wagtendonk and De Jeu 2007; Tzvetkova et al. 2012). There are only few successful attempts of analysing the methodological problems or indicating pitfalls that may occur if a good practice of Mobile GIS is not used (Campana 2016).

We think such a summary is needed, because the regional field prospection, in the form as we know it, might change in the near future in parallel with changes in GNSS technology. By the comparison of current possibilities, we would like to point out the quality of this technique, new tools, and would like to discuss the role of professional GIS analysts in it. We are convinced that current developments in GNSS, equipment and characteristics of mobile GIS applications have to be discussed to place the current field survey techniques in their broader context and shed light on their future development.

Past Field Surveying Techniques

The history of settlement pattern research has been summarized many times, so there is no need for detailed discussion (e.g., Alcock and Cherry 2004; Banning 2002; Campana 2016; Keller and Rupp 1983; Layton and Ucko 1999; Sanders 1999). The beginning of regional field survey in archaeology goes back to 18th century (Banning 2002: 2). As a separate research method, it appeared in the early 20th century (ex. Huntington 1908; Williams-Freeman 1915). Since the 1930s, great interest was placed on the settlement pattern studies (Adams 1965; Ford and Willey 1949; Wedel 1953). For the purposes of this article, it is relevant to mention that, in the 1950s, Gordon R. Willey working in Virú Valley proposed a workflow that is still recognized and utilized today. It included: analysing the aerial photography previous to fieldwork; mapping sites with the help of an epidiascope, with pencil and paper; field checking and measuring features not visible on aerial photos, and mapping them on previously prepared maps with the use of a compass (Willey 1953: 3–5). Similar approaches were developed in other regions (e.g., Adams 1965; Tolstov and Orlov 1948).

Through 1960s the processual paradigm shaped what could be learned from settlement pattern studies (ex. Binford 1964), which resulted in post-processual criticism (Wilkinson 2003: 4–7). Starting from

1970s, the so called "Second Wave" of prospection, proposed a methodology in which the improvement of reliability of data collection was the main focus (Campana 2016: 115). In 1990s and 2000s, a critique of the "Second Wave" in field prospection started (Campana 2016: 115). It seems that the technological development of non-invasive documentation tools was an answer to some of the limitations confronted by archaeologists. In 1998, the first use of mobile, computer applications deployed in the field was presented by N. Ryan and colleagues (1999), followed by other field researchers (i.e. Pundt 2002; Tripcevich 2004). Recently S. Campana (2016: 118) has argued that a "Third Wave" of field surveys should be distinguished.

Nowadays a majority of projects include GIS in the research, while almost all field prospection projects use mobile GIS during their surveys in some degree. Their main focus is to find new sites, verify areas of interests found through remote sensing, study the landscape, and also document archaeological features and artefacts visible on the surface in endangered areas (i.e., Bogacki et al. 2010; Buławka 2018; Buławka and Kaim 2016; Ejsmond et al. 2015; Tripcevich and Wernke 2010; Tzvetkova et al. 2012). There are many examples of research projects entirely relying on Mobile GIS techniques. Thus, there is a need to re-evaluate the development of GNSS in order to check how GPS accuracy has changed since the "Third Wave" has begun (Campana 2016).

In many areas of the world, the major problem is looting of archaeological sites or their rapid destruction due to urban sprawl (e.g., Brodie and Renfrew 2005; Casana 2015; Chyla 2017; Contreras 2010; Lauricella et al. 2017; Tapete et al. 2016). This has led to development of workflows that incorporate remote sensing, in which several thousand possible sites can be discovered (e.g., Campana 2009; Casana 2014; Hritz 2013; Lambers and Zingman 2013; Menze and Ur 2012; Sonnemann et al. 2017; Traviglia and Torsello 2017).

The review of the papers published recently indicates that one of the major challenges of current and future regional surveys is the possibility to verify in the field new archaeological sites identified through remote sensing. It is clear that in order to achieve this, greater speed and accuracy are required than ever before. Field survey is time consuming and that has always been a big challenge for archaeologists (Willey 1953: 2). We think that this could be solved by an implementation of fast surveying techniques and workflows. The problem is, however, what are those "fast surveying techniques" in regard to the state of the art of current GNSS and how reliable are they? In order to answer these questions, we should evaluate how the development of GNSS articulates with our need for speed and accuracy.

The Brief GNSS History

The first Global Navigation Satellite System (GNSS) available in the world is Global Positioning System (GPS NAVSTAR). Following its deployment, some other satellite navigation systems have been developed (Hofmann-Wellenhof et al. 2008). The performance of the above-mentioned systems is augmented by national ground-based and satellite-based systems (van Diggelen 2009: 218, 297, Tab. 10.1). Since this paper is mainly concerned on the development of GNSS for archaeological purposes, the detailed analysis of all navigation systems is unnecessary. Analysing the topic from the perspective of GPS should be enough to give the reader a good understanding of development of the technology. The detailed history of GNSS could be found in several authors (i.e. Hofmann-Wellenhof et al. 1992, 1993, 1994, 1997, 2008; Madry 2015; Seeber 2003; Teunissen and Montenbruck 2017; van Diggelen 2009; Xu and Xu 2016).

The Early Civilian GPS Capabilities

GPS was a military project of the Joint Program Office, which was directed by the US Department of Defense to establish a positioning system in 1973 (Hofmann-Wellenhof et al. 2008). In 1978 the first satellite was launched (van Diggelen 2009: 229). After 1983, due to an incident with the Korean Airlines Flight 007, GPS was allowed to be used for civilian purposes (Hofmann-Wellenhof et al. 2008: 311, 332-333, Table 9.6, 9.7). In 1993 the initial 24 operational satellites were launched and two years later full operational capability was reached, but the general accuracy of positioning was low. Only one civilian GPS signal was available. It was broadcasted as L1 C/A signal (L1 Coarse Acquisition) within the 1575.42 MHz frequency. The low performance, however, was caused not by technological barriers of that time but by a "Selective Availability." It was an intentional data error on ephemeris and the clock of the satellites (Hofmann-Wellenhof et al. 2008: 311, 319-322). In the 1990s, the main problem in professional equipment was to achieve precise measurements in the shortest possible time. This, alongside with the low GPS accuracy caused the development of different ground-based and satellite-based augmentation systems.

First, the assisted GPS (A-GPS) or assisted GNSS (A-GNSS) should be mentioned. It is a ground-based augmentation system, in which the receiver gets its general location from the network of cell towers. Also, most of the information required for GPS positioning is sent by the cellular network: almanac, ephemeris, frequency and precise time. Using A-GPS the only missing ingredient to measure a position of the receiver are the signals sent by satellites themselves (van Diggelen 2009: 1–2, Figures 1.2).

A more precise augmentation system already available in the 1990s was differential GPS (DGPS). It relies on two or more receivers. First, one has to have a known static geographic location. It constantly measures new coordinates and then compares them to the known position, calculates corrections and sends them to the other receiver (the rover). This technology was implemented for aircraft and other fields requiring precision (Hofmann-Wellenhof et al. 2001: 136-141, 186-189; 2008: 415-416, 436). In archaeology, however, there were also a number of successful attempts to use this technology (Colosi et al. 2001; Hoelzmann et al. 2001; Vlahakis et al. 2002).

There were different methods relying on the above-described concept, which could be described as relative positioning (Mezera and Hothem 1995; Hofmann-Wellenhof et al. 1992, 2001, 1992, 2008; Hofmann-Wellenhof and Remondi 1988; Remondi 1985). Initially, the data had to be uploaded to the computer. On-the-fly (OTF) techniques were developed later (Hofmann-Wellenhof et al. 1994: 161, 168). Nowadays, online postprocessing services are available, which rely on the International GPS Service for Geodynamics (IGS, currently International GNSS Service) developed since 1990 (Beutler et al. 1996; Hofmann-Wellenhof et al. 1994: 69).

In the 1990s new types of relative positioning were also developed - real-time kinematic relative positioning (RTK) and wide-area RTK (Hofmann-Wellenhof et al.1997: 137, 138, 144; 2001: 135; 2008: 431-439). In these methods, the precise coordinates could be measured OTF with use of corrections transmitted from the continuously operating reference stations (CORS) (at first via radio). This technology evolved with time in parallel to changes in GNSS and other technologies.

GNSS and the Geospatial Revolution

A new era of satellite navigation began in early 2000s. First, in the May 2000 thanks to the presidential order of Bill Clinton, a "Selective Availability" (SA) was turned off (van Diggelen 2009: 229). This was the first and the largest leap in increasing GPS accuracy. The removal of SA was crucial, because previously the increase of accuracy could only be done with specialized equipment. Ever since, a regular GPS user with basic skills could enjoy 10 to 25 meter accuracy. This event had a serious impact on the GIS community in archaeology and other disciplines.

Three years later GPS appeared in the first palmtops and mobile phones. A rapid growth of the number of GPS receivers available in smartphones was observed (Schreiner 2007). In 2007, over 70 million of them were sold. Since many of them were programmed with the Android system (Lee 2012; Rogers et al. 2009: 3), new navigation and mapping applications were created, some of them available at no cost.

Simultaneously, there were improvements in professional equipment. First of all, in 2003, GPS Wide Area Augmentation System (WAAS) started to be available for the GPS users. WAAS is an example of a regional Satellite Based Augmentation System working in the North America (Hofmann-Wellenhof et al. 1997: 347-347; 2008: 348). Also, new civilian signals were introduced. In 2005, satellites equipped with the second civilian signal (L2C) were launched (van Diggelen 2009: 310; Hofmann-Wellenhof et al. 2008: 334-335), but the signal was not broadcasted until 2010 (Doberstein 2012: 244). Currently, civil L2 signal has pre-operational status, it is broadcasted on a 1227.6 MHz carrier frequency (Hofmann-Wellenhof et al. 2008, 334-335, Table 9.6, 9.7). It provides greater position accuracy even in partly covered areas, also when used together with another signal, it enables the user to eliminate the ionospheric errors (van

Diggelen 2009, 24, 310). A gradual slow increase in precision of GPS was visible until 2013 (Madry 2015: fig. 3.19). In 2014, the third signal (L5) appeared. It is broadcasted on 1176.45 MHz carrier frequency (Hofmann-Wellenhof et al. 2008: 335-336, Table 9.6, 9.7). Its initial testing was conducted in 2009 (GPS 2014), and the current status is still pre-operational.

Current GNSS Trends and Future Possibilities

In 2009, it was announced that a fourth civilian signal will be broadcast in GPS III generation satellites – L1C. It will be broadcast on the same frequency as L1 C/A (1575.42 MHz carrier), but it will be different. It is planned that Galileo and other civilian constellations will broadcast the L1C code, which will enable greater interoperability (GPS 2014; Hofmann-Wellenhof et al. 2008: 336, Tab. 9.5; Madry 2015: 55). In the last decade other GNSS systems have been developed, such as a European Galileo (since 1994) (Hofmann-Wellenhof et al. 2008: 365-395), Russian GLONASS (Hofmann-Wellenhof et al. 2008: 344), a Chinese BeiDou 2/Compass (since the 1970s) (Hofmann-Wellenhof et al. 2008: 401-403), a Japanese QZSS (Hofmann-Wellenhof et al. 2008: 409-413), and an Indian IRNSS (Hofmann-Wellenhof et al. 2008: 414). The accessibility of different constellations create an opportunity for GPS receivers to integrate all the systems together. Recently, several teams have argued that the development of triple frequency GNSS or availability of different constellations will cause the Real-time Precise Point Positioning (RT-PPP) to be an alternative to RTK (Choy et al. 2015; Rizos et al. 2012; Ye et al. 2016). This method of positioning is not new; however, its development was possible due new capabilities.

After 2020, we are expecting gradual changes. The recently published 2017 Federal Radionavigation Plan confirms that when L2C and L5 signals are available in 24 satellites the transmission of the codeless/semi-codeless signal will be gradually stopped. It is planned that L2C signal will be coded in 2023. In 2024, the full constellation carrying L5 signal will be achieved, which will be followed by transition to coded signal. The L1C will be also coded (DoD / DHS / DOT 2017: 58-59, 105). According to published data, it will force equipment to be changed to receive these new coded signals (Hegarty 2017: 217).

In next seven years we are going to face a new era of GNSS. This will definitely have an effect on the GIS community. From the perspective of contemporary problems of financing archaeological projects, it could have a negative effect. In our opinion, it could trigger the bigger emphasis on the use of L1 C/A capable receivers. The discussion on the future of mobile GIS from the perspective of smartphones seems inevitable. Yet, it dangerous to speculate whether the availability of L1C signal will be beneficial in smartphone technology or not. This sector of the market will keep developing through the next decade though (European GNSS Agency 2017: 6, 7, 10-12).

It is obvious that some problems should be taken into account. First of all, the GNSS receiver is stacked together with other receivers in smartphones (Bluetooth, WIFI, 3G) in one chip. The design of those chips has to face the problems of energy consumption and demand of miniaturization together with the performance of other functions (Gramegna et al. 2006; Kadoyama et al. 2004; Uvieghara et al. 2004). The review of papers indicates that currently the indoor positioning is more important than outdoor capabilities in cities. This is achieved by use of gyroscope, compass, accelerometer, A-GPS and Wi-Fi-based positioning (Hsu et al. 2016; Vaughan-Nichols 2009; Zhao 2002). For a long time, however, there was no need to develop the GPS chips in order to use different GNSS constellations or signals in smartphones. But, recently this became necessary and the chip architecture that could handle different GNSS constellations was created (Mair et al. 2015). Perhaps, the better performance of L1C signal indoors and in cities could trigger the creation of cheap smartphone chips too.

Even though the development of GNSS is still in progress, nowadays, archaeologists can use receivers with accuracies ranging from 5 m to 1-3 cm. The regular handheld GPS receivers can have the accuracy of 3 m, which with smartphones and tablets (about 5 m) (Zandbergen, 2009), fill about 99% of the market. While, cheap GIS tools with SBAS are able to reach 1.5 m, most of the sellers also provide additionally paid post-processing service, which give further improvement to sub-meter accuracy. Also, for precise measurements RTK and RT-PPP can be used. It is unclear how the future development of GNSS will change the available accuracy or influence the preference of specific surveying methods in archaeology. It is clear, however, that less time-consuming techniques of prospection than RTK or RT-PPP are needed for the regional survey (Gill et al. 2018).

Within the spread of GPS in archaeology several factors are important when we compare the past and current possibilities. First is the price of the receiver in accordance with its accuracy. Initially, the price of a GPS receiver for civilian use was ca. 20,000 U.S. dollars (Hofmann-Wellenhof et al. 1992: 122). The price decreased, but until 2000s early survey projects had to deal with high equipment prices and low accuracy caused by SA. Nowadays, however, the 5-10 meter GPS accuracy, which is appropriate for regional surveys, can be achieved with cheap devices and can be performed by users that need very little training.

Mobile GIS Tools in Archaeological Prospection

Nowadays for field prospection, understood here as the identification and documentation of new archaeological sites on regional scale, one can choose from a spectrum of tools and applications. Since 2013 (Google 2013) a variety of software dedicated to tablets and smartphones became a main interest of developers. The new tools and software improved on site measurements and cabinet works (Campana 2016).

In 2014, Chyla and Bryk proposed a table which analysed functions of tools used during archaeological field prospection on a regional scale. They analysed three types of tools: GPS receivers (Joglekar and Sushama 2008), smartphones with mobile GIS applications (a new trend in GIS software development), and Personal Digital Assistants (PDA) with GNSS receivers. The table described possibilities of each tool with characteristics which are mostly needed by archaeologist during their fieldwork, such as: describing documented features, documenting features as polygons; changing coordinate system of documented data; the possibility to create the workflow without the need of being connected to the internet; the possibility of different users working at the same time, editing and collecting information in the same datasets at the same time; tools' battery life (suitability for long time data collection without charging); tools' durability in the field; the possibility of connection to reference stations that could help to increase accuracy of the measurements. Other characteristics, like using your own rasters, importing desktop created data to the tool, navigation to areas of field survey or exporting documented data to the computer are not listed, because all tools have such options.

One can also observe growing interest in working with UAV and photogrammetric data in the field (including use of the LiDAR and ALS survey results). At the same time, the quality of data acquisition stopped being the main focus for the archaeologists during regional field prospection, as the tools can connect to reference stations and add corrections to the positions during post-processing work as well. Also, an external GPS for smartphones and tablets were introduced, which can propose reliable measurements for such a type of surveying (AFS 2015).

The described characteristics of tools used in regional surveys (presented in the table 1) show the biggest differences between them.

GPS

A simple handheld GPS navigator is relatively popular tool used in archaeological field prospection. It supports single satellite frequency, but it connects with many constellations and has access to SBAS. It can position the user on previously uploaded maps and allows uploading earlier prepared points. This helps to orient users in the landscape. GPS also allows collecting new data as points in any coordinate system, with short text information. It allows to export data to *gpx format, which is possible to display in GIS. Additionally, it is possible to edit, verify and update data in the GPS while still in the field. GPS allows the user to save data as points or tracks (lines). This allows marking areas of archaeological site before or during field survey. GPS works without any internet connection, but it does not allow simultaneous work of different groups and real time, export of data to the cloud or external server. The design of the tool itself was made for fieldwork, so it has high durability and usually long battery life. GPS does not have a possibility to support documentation with UAV or with photogrammetric models (Table 1).

Tool	Attributes	Polygons	Possibility to choose coordinate system	Work without internet	Groups working at the same time	Battery life	Field durability	Connecting to reference stations	Working with UAV	Using photogrammetric data
GPS	X	◊	✓	✓	X	✓	✓	✓	X	X
Application on tablet or smartphone	✓	✓	X	◊	✓	X	X	◊	✓	✓
Mobile GIS on GNSS tool	✓	✓	✓	✓	✓	✓	✓	✓	X	X

Table 1. Table represent the most important aspects of using mobile GIS and tools most often used in archaeological field prospection (based on Bryk and Chyla 2014: 23, with changes).

Legend:
✓ – function exists
X – function is not existing
◊ – function exists under special conditions

Mobile Applications on Smartphones and Tablets

There are many smartphone or tablet tools for daily or professional design. But, even the rugged GNSS tablets, specially created for the professional topographic surveys, without the external antenna, can only use L1 C/A code. At the moment, the GPS with SBAS does not occur in non-professional equipment (except handheld GPS receivers). There are some examples of wide screen GNSS tools with dual frequency, but they have to be linked with PDAs. There are many operating systems for smartphones and tablets, as well as a large variety of mobile GIS applications, working on those OS. They are already capable of using different satellite constellations; however, their inbuilt receivers do not support many of the functions. A regular smartphone, however, can function as a RTK controller when an external receiver is used (via Bluetooth) or can be used to coordinate UAV survey (Table 1).

Applications for smartphones and tablets allow locating and navigating users thanks to an inbuilt GPS (Zandbergen 2009), but it is not recommended to start the documentation without an external antenna (AFS 2015). Several types of applications with spatial capabilities could be distinguished. It is not possible to give a comprehensive list of all mobile applications, because it is a fast-developing field. There is a vast field of non-GIS applications that collect spatial data (Twitter, Facebook, etc.). The most popular types are car navigation, tracking applications used for geocaching, compass and GPS viewers, etc. The most useful types include databases with spatial capabilities, GIS applications that can visualise different spatial data but only map points and tracks, GIS applications that allow mapping different geometries, applications supporting different geodetic calculations, applications used to configure a RTK controller, conduct UAV survey or make 3D model.

Most popular applications allow preparing the dataset beforehand, which includes all geometries with attributes. However, it is not possible to change coordinate systems in the field. As a default, applications run on prepared basemaps, satellite images, and WMS services. Many of them, in order to export the data, use cloud services. Therefore, it is obligatory for those tools to be connected to internet. On the other hand, it allows different groups of researchers to work on the same project at the same time, as data is sent in real time. This is done by Wi-Fi or cellular network data transfer, which is not problematic in places which are covered by 3G, 4G, or LTE. However, problems occur when the research area is outside such zones. In such situations the application will update the data it reconnects to the network.

Data is saved in many different formats, depending on the application and is available for cabinetwork through a browser or GIS program connected to the Internet. Also, it is possible to download the data and add it to a desktop GIS. Smartphones and tablets are not durable in the field and their battery life is usually low. There is a need of additional external power bank and accessories to protect the machines. New applications for smartphones and tablets allow connecting to cameras on the UAV in real time or pre-program flight paths (i.e. DJI GO, Litchi). Also, they allow doing 3-D scanning and collecting photogrammetric data (i.e. 123D Catch).

As for software which could be used by archaeologist on smartphones or tablets, one could choose a variety of them (i.e. GoogleEarth, ArcCollector, Survey123, QField, Locus, WolfGIS, SW Maps, Mappt, to name just a few) (Sikora 2013). There are also many applications created by archaeologists (i.e. FAIMS Mobile, Archeotracker) (Ross et al. 2013; Sobotkova et al. 2015). The goal of such applications is to make field documentation workflow easier, however very often such applications are not updated. In the time when phones and tablets systems are upgrading at least every half a year, there is a danger that not regularly updated archaeological applications could become outdated. Additionally, for the same reasons, it is very difficult to describe specific applications. What we write today might not even be valid tomorrow.

Personal Digital Assistants with GNSS Receivers

This category of equipment is variously described by different vendors. The name examples include handheld GIS data collectors, handheld computers with GPS/GNSS, handheld GNSS systems, PDAs, or controllers (used in RTK). In general, they are professional rugged portable handheld devices with GNSS or GIS capabilities. Currently PDAs differ in capability within frequencies, augmentation systems, satellite constellations, CPU performance, and size. Some have single frequency and SBAS augmentation systems, others could have dual frequency. PDAs are also used as RTK controllers. This enables the user to achieve different accuracy from 5 meters through 1.5 meters to several decimetres and all the way to < 1 cm. Mobile GIS Applications designed for PDAs seem to combine good accuracy of GPS measurements with the capabilities and comfort of use of smartphone/tablet applications. They allow the user to pre-program the interface and databases with attributes before the fieldwork but also to change them during the process. Applications like this, work the same as desktop GIS software, and they allow uploading and documenting field data as points, lines, or polygons with attributes. Additionally, it is possible to define attributes to create fast and accurate descriptions of documented sites, features or artefacts from regional or detailed scales (Chyla 2015). The coordinate systems can be chosen by the user, also the software can propose basic coordinate transformations if needed. PDAs do not have to be connected to the Internet. However, such an option allows different groups to work simultaneously on the same project (the same as applications on smartphones and tablets) or can allow working with WMS basemaps. PDAs, similar to handheld GPS, are dedicated for field work and therefore they are resistant to atmospheric conditions and their battery life is long. They can be connected to reference stations in real-time, or it is possible to post-process data after. For PDAs, UAV and photogrammetric software has not been developed; however it is possible to upload results of their work to mobile GIS applications. There are, however, PDAs working on phone/tablets dedicated systems (i.e. Trimble TDC100, Leica Zeno 20), which make it possible to use such applications if the performance of the PDA is adequate. Additionally, quality of the measurements done by such tools might allow one to support the creation of photogrammetric models or to register aerial photos (Table 1).

Summary

The table compares various tools used by archaeologists and their characteristics which are, or probably will be, most often used in the regional scale field prospection (Table 1). All of the above-mentioned tools share the need to prepare the data before starting fieldwork. The workflow focuses on proper preparation of the datasets and attributes in the office. One can notice that the workflow connected to field work with GPS, PDAs, or smartphones/tablets might differ quite a lot. Fieldwork with the use of handheld GPS for example, seems to be still based on paperwork. PDAs and smartphones/tablets workflow is based on digital data and proposing automatic, easy workflows.

All described tools fit the current needs of archaeological fieldwork. Although smartphones/tablets and PDAs have more options for accuracy and enable one to create full descriptions of documented features

In the near future, it seems that mobile GIS software on smartphones and tablets will dominate large scale field surveying thanks to possibility of multi-user cooperation (crowd collection of data), the variability of applications, and the flexibility of workflows. Crowd data collection might make prospections faster; however, it is required to properly prepare datasets and attributes by a manager/administrator, as any changes during the work might be problematic. It is important to stress that the use of mobile GIS on smartphones separates the role of data creator and data collector. This allows archaeologists who are not GIS specialists to use applications dedicated just for their needs.

Characteristics such as battery life and field durability and precision of measurements speak in favour of GIS applications on PDAs. On the other hand, as mentioned above, tablets dedicated for topographic surveys are also available on the market, although their cost makes them less accessible. Additionally, it seems that the software developed for smartphones and tablets will become the main working tools in field surveys in general (SAMSUNG 2017; GPS World Staff 2014; Trimble 2014), as developers withdraw from upgrading software dedicated for PDAs (see Windows Mobile Life Cycle - Microsoft 2017; ArcPad Life Cycle – ESRI 2017). PDAs also have one, very important advantage. They allow full access and control over collected data, the place where it is exported and where (and with whom) it is shared. There is no need to upload data to the server. It is possible to access the data directly in the tool memory from the PC. This is available also on the tablets and smartphones; however, the process is not intuitive and automatic. This might change when smartphones become more commonly used than laptops or desktop PCs.

However, many questions arise from the analysis of the table. The most important is: are archaeologists using the full capabilities of described tools?

Conclusion and the Discussion About Current Possibilities and Future Needs

One of the main tasks of the archaeologists – localisation and mapping of archaeological heritage based on observations – has always been a challenge, especially in light of landscapes' dynamic change. Tools with inbuilt GPS become a convenience, which not only helps to position the user in the landscape but also allows for increasing measurement accuracy. They allow the user to integrate digitized archival paper documentation, marking areas of interests, documenting and mapping features in the field (Bryk and Chyla 2014: 25).

Mobile GIS allows one to document and map new archaeological sites and artefacts' distribution. It also gives the possibility of editing previously updated data. The variety of data types that can be collected is limitless. Thanks to such solutions results can be displayed immediately, analysed, and presented in final reports.

As we demonstrated, the recent developments in archaeological field survey clearly correspond with changes in GNSS technology. During the Second Wave of archaeological field survey a variety of measuring techniques were used. The problem, however, was to connect collected data with geographical coordinates. The presence of GPS was not associated with the increase of the measurement's accuracy; the main subject of the 1990s discussion among field surveying archaeologists. Since 2000, the Third Wave was connected with the geospatial revolution and the increase of positioning accuracy. As a result, the availability of data and the access to different sensors re-defined the surface survey.

With the arrival of the Fourth Wave, the main focus will be on the possibility of mapping higher number of new archaeological sites in shorter amounts of time with methods such as crowd data collection and remote sensing with the use of satellite images or drones.

So far, in our opinion, there is no Mobile GIS application that is able to meet all expectations of the archaeologists. However, there are applications created by archaeologist and for archaeologist, which are fulfilling many needs of fieldwork. Such applications do not necessarily have to have the possibility of sub-centimetre accuracy in measurement, but mostly should be flexible enough to support the different types of data that archaeologist document, create, or use. Software should also allow for modification of database schema. New directions indicate that such tools should provide possibility for simulation works with UAVs, photogrammetric data, analyse collected information in 3D and also to display archaeological data not only for researchers but also to the public.

If the combining of multiple signals from the different satellite constellations become an everyday practise, then the smartphones will exceed the PDAs with the available capabilities. In addition to that, the ability for multiple users to collect data on the cloud simultaneously will become a common solution for large, regional scale field surveys, which are time limited. Especially if it can be done using the tool that most of us have - smartphones or tablets, there will be no need to expand budget with high cost, specialized tools. We predict that these characteristics will change not only field prospection methodology but also the data collection process. Our current work already raises questions about the roles, skills and abilities needed for not only data managers, who creates field projects as applications, but also data collectors, who will be responsible for filling out field information.

Conclusions of the session "Mobile GIS and field survey - current possibilities, future needs", as mentioned at the beginning of the paper, are strongly suggesting that regional field prospection will change in the near future, in connection to changes in GNSS technology. The paper broadened the topics discussed during the session. Presented comparison of available tools and their characteristics, together with current trends in GNSS technology not only shows what are current possibilities, but possible direction that archaeologist are heading to. This direction seems to lead to the fast, low cost techniques, in which role of professional GIS specialist is a manager not a data collector. The questions still need to be asked out loud, whether it is a right direction.

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Accessing the Inaccessible: Detailed 'Off-Site' Archaeological Survey Using Satellite Imagery and GIS at the Hatnub Travertine Quarries, Egypt

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Abstract

Archaeological sites, trails, and roads are traced using satellite remote-sensing, but landscape archaeology often requires detailed survey of much smaller features. At the Hatnub travertine quarries in the Egyptian desert, an 'off-site' survey of small diffuse archaeological features was undertaken using high-resolution, pan-sharpened satellite imagery with contrast stretching in obscured areas. Comparison with recent field survey data demonstrated that this remote-survey process was fast, reliable, and generally accurate, with a 93% success rate identifying known features, and false positives estimated at 13%. The resulting digital plans provide an accurate initial record of an imperilled landscape at a level of detail that has not previously been attempted using remotely sensed data. This ensures that future ground-truthing and investigatory fieldwork is targeted at the most important remains and can be combined with mobile recording techniques that modify the remote sensing, survey data during 'on-site' fieldwork.

Keywords: GIS, remote-sensing, survey, satellite imagery, Egypt, mobile-GIS

Introduction

Archaeological investigations of landscape and 'non-site' archaeology have been widely established as a means of answering local and regional research questions and contributing to debates about settlement distribution, transport, and resource procurement (For recent examples see papers in Burgers, Kluiving and Hermans 2016; Campana, Forte and Luizza 2010; David and Thomas 2008). This research depends upon the existence of consistent information concerning sites, anthropogenic features (including archaeological features of all periods and other human interventions in the landscape) and historical traces across the locality or region that is under investigation.

In countries like Egypt, where local or national databases of archaeological remains are non-existent, difficult to access or still in development, or where the nature of the archaeological record predisposes excavators to focus upon certain sites or types of site, it can be difficult to obtain the necessary landscape data to undertake regional archaeological research (Fradley and Sheldrick 2017: 796; Tassie and Hassan 2009; Weeks 2008: 18-19; Wendrich 2010). This places concomitant restrictions upon landscape archaeology and regional analyses in the country (Abu-Jaber et al. 2009: 3; Jeffreys 2010: 106-108; Parcak 2008). This issue, together with the ongoing threat to archaeological remains, has prompted many archaeologists and Egyptologists to begin recording anthropogenic features at the local and regional level using traditional epigraphic and archaeological surveying techniques (see for example Bloxam et al. 2014; Darnell 2013; Darnell and Darnell 2013; Förster and Riemer 2013 ; Förster 2015; Heldal 2009; Heldal et al. 2009; Kelany et al. 2009; Kemp and Garfi 1993; Riemer 2013; Rossi and Ikram 2013; Shaw 2006; 2010; Wilson and Grigoropoulos 2009).

The extent and quantity of archaeological remains that can be recorded using these methods is limited by the length of the fieldwork, the resources of the project, and the size of the concession within which it has permission to work.

Archaeologists working on Egyptian landscapes have been making use of satellite imagery since the 1980s (El-Baz 1984; Wendorf, Close, and Schild 1987). Although these methods were initially limited by the resolution of the imagery (Bubenzer and Bolton 2013: 72-3), more recent work has made use of increasingly high resolution satellite imagery to locate and monitor archaeological sites (Mumford and Parcak 2002; Parcak 2007; 2010; Parcak et al. 2016), record roads (De Laet et al. 2015), and larger anthropogenic features (Ejsmond, Chyla, and Baka 2015; Ejsmond et al. 2015: 619).

This research has repeatedly demonstrated that the resolution of the satellite imagery is of greater importance in the identification of small archaeological features than its multi-spectral component (Bubenzer and Bolton 2013: 66; De Laet et al. 2015: 293-5; Dore and McElroy 2011: 15) and that pan-sharpened imagery is preferable to individual multi-spectral bands because it is higher resolution (De Laet et al. 2015: 289). Research has also shown visual inspection to be more effective in the identification of smaller archaeological features than automatic processing (Dore and McElroy 2011: 16).

With the increasing availability of very high (sub 0.5 m) resolution satellite imagery, it is now cost-effective to record in detail far smaller archaeological features than was previously possible, using remotely-sensed satellite imagery in Geographic Information System (GIS) software. This type of 'remote-survey' should prove substantially faster than 'on-site' field survey and enable subsequent fieldwork to focus upon targeted 'ground-truthing' and the investigation of questionable or interesting features identified during the survey.

This paper describes the methods used in the initial 'off-site' remote-survey of 100 km^2 of the Hatnub desert quarrying landscape using Worldview-3 high resolution (0.4 m) pan-sharpened satellite imagery in ArcGIS 10.4, and assesses the accuracy of the remote-survey in comparison to field survey records of the same area made by Shaw (2010).

The Hatnub Travertine Quarries

The travertine (or 'Egyptian alabaster') quarrying region at Hatnub was the pre-eminent ancient source of that highly prized translucent white stone (Harris 1961: 77). The quarries are located 17 km from the Nile river, southeast of the site of Amarna in Middle Egypt (Figure 1) and were rediscovered in 1891 by Howard Carter and Percy Newbery (Shaw 2010: 3-5). The inscriptions in the three main quarries (named P, T, and R) were first published in Blackden and Fraser (1892) and the definitive publication of the Hatnub texts was undertaken by Anthes (1928), although recent epigraphic work in Quarry P suggests that more is to be found (Enmarch 2015; Gourdon 2014).

The three main quarries and the road leading to them were recorded in Petrie's (1894 3-4: pl. 34) and Timme's (1917: 34-47: pl. 1-8) plans of the nearby site of Amarna, but both of these maps were small in scale and neither researcher made any attempt to comprehensively record individual archaeological features. Harrell (2001) recorded the quarries at the north end of the Amarna plain (Figure 1), but did not extend his survey further south. The most extensively investigated area is the concentration of tracks, huts, shelters, windbreaks and cairns around Quarry P, 890 m^2 of which was surveyed by Shaw (2010) between 1985 and 1994. This was an exhaustive survey, which produced detailed plans, but Shaw was only able to record a small fraction of the landscape. A short visit to the site or cursory review of satellite imagery shows that the tracks, shelters, and cairns extend over at least 100 km^2 in a diffuse pattern around all the travertine quarries and along the c. 17 km road between them and the Nile valley (Figure 1).

The Hatnub landscape and its many unrecorded quarries, hut-clusters, trails, paths, cairns, and shrines forms what has been called a 'quarry complex' (Bloxam 2011: 152). The study of this complex has the potential to reveal new logistical, practical, and cultural aspects of quarrying and to contribute to international debates about the procurement of resources and the role of peripheral landscapes in ancient societies. To address these complex archaeological questions and undertake detailed analysis, it is necessary to first record all the visible archaeological features across the entire 100 km^2 study area.

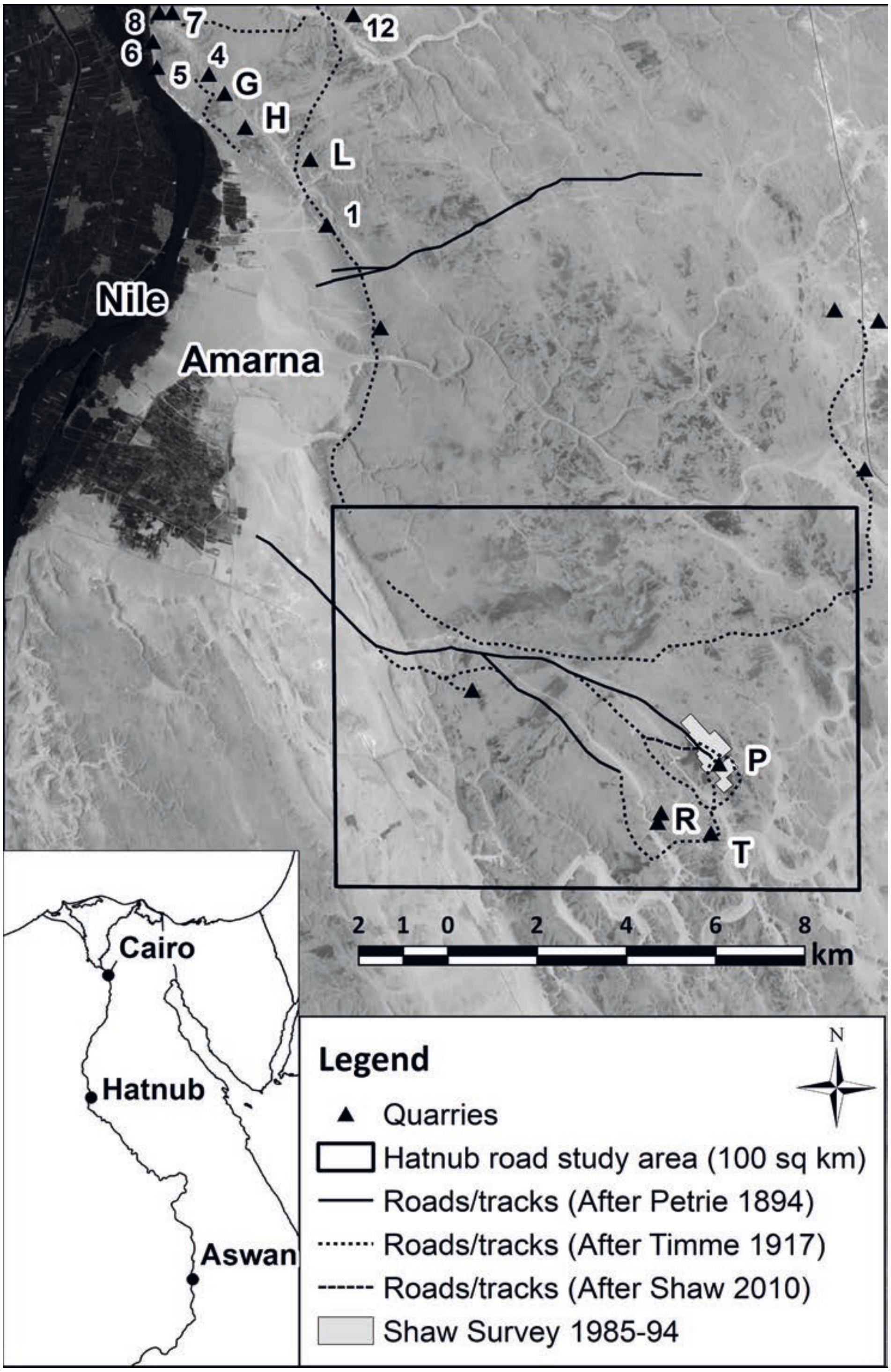


Figure 1. The location of the Hatnub travertine quarries, Quarry P, the 100 km^2 study area and the area surveyed by Shaw (2010) in 1985-94. Lettered quarries were recorded by Petrie (1894) and numbered quarries by Harrell (2001) (Underlying Landsat 8 data from the United States Geological Survey).

Methods and Materials

The Hatnub landscape comprises an open desert, with limited rainfall and almost no vegetation, but a large number of small, diffuse archaeological features. Modern activity is restricted to certain specific quarrying areas. This makes it an ideal landscape to test the use of detailed 'off-site' archaeological survey using high-resolution satellite imagery. Naturally in other countries or regions with different ecological and geomorphological attributes, alternative techniques would be required to record archaeological remains obscured by cloud, vegetation (whether natural or agricultural), or modern structures.

Materials

Google Earth was used initially to confirm the visibility of small archaeological features across the Hatnub landscape before any commercial satellite imagery was purchased or archaeological features recorded. A number of issues with Google Earth and other freely available satellite imagery make it unsuitable for this large-scale, detailed, archaeological survey. Some freely available satellite imagery (such as Landsat and similar data available from the United States Geological Survey) is of medium or low resolution (i.e. no greater than 10-15 m) and the small (typically 1-5 m) archaeological features at Hatnub would not be visible in it. While other higher resolution free satellite imagery (such as Google Earth, Bing Maps, and other similar providers) comes with restrictions on the processing or availability of specific images. Although these issues may not be prohibitive or can be overcome under certain circumstances, the most significant problem with free high-resolution satellite imagery is its often poor geolocation and the tendency for imagery to shift location over time (Parcak 2009: 363; Pedersén 2012: 388). This clearly makes even high-resolution, free satellite imagery unsuitable for the very precise and accurate large-scale survey of small archaeological features that is at the heart of this project.

This project used a 4-band, pan-sharpened 0.4 m resolution satellite image created from blue, green, red and near infra-red 1 multi-spectral bands pan-sharpened with the panchromatic band of the DigitalGlobe Worldview-3 satellite (DigitalGlobe 2017) image recorded on 9 June 2016. The four multi-spectral bands have a sensor resolution of 1.24-1.38 m (ground sample distance) and the panchromatic band has a 0.31-0.36 m sensor resolution (European Space Imaging 2014: 38). The pan-sharpening used an enhanced resampling kernel and the image was radiometrically-corrected, sensor-corrected (European Space Imaging: 24), and orthorectified using a 4 m resolution digital surface model (DSM) created from stereo-pair Worldview-3 imagery of the same area. It was not possible to georeference the Worldview-3 image with ground control points, as these were not available at the time. European Space Imaging (European Space Imaging 2014: 24) calculates that when orthorectified with SRTM data, which now has a resolution of c. 30 m (USGS n.d.), this type of Worldview-3 product has an accuracy of 6.6 m RMSE. Since the satellite image used in this project was orthorectified using a 4 m stereo-pair DSM, it should be better than 6.6 m RMSE, although currently it is not possible to calculate the precise error. The 100 km^2 Worldview-3 image purchased from European Space Imaging will not only provide consistent geolocation of the surveyed archaeological features but is also the most accurate source of geolocational data available to the project at present.

Survey Method

During the remote-survey the archaeological features were located using visual inspection of pan-sharpened Worldview-3 0.4 m resolution satellite imagery in ArcGIS 10.4 software. Prior to visual inspection, a 100 m^2 survey grid was overlaid on the 100 km^2 Worldview-3 image using the 'Create Fishnet' tool in ArcGIS 10.4 in order to provide a systematic grid for visual inspection and provide the basis for future sampling. A 'Surveyed' field was added to the grid attribute table. Upon completion of the visual inspection of a grid-square the 'Surveyed' attribute of that grid square was changed from 'Null' to 'Yes', tracking the progress of the research.

Archaeological features located in the Worldview-3 imagery by visual inspection were digitised as vector polygons and points or lines. Each contiguous polygon feature (such as a wall) was digitised separately as a vector polygon with a unique number. These polygons were grouped into archaeologically meaningful structures (such as huts, shelters or cairns) and recorded as point data with unique numbers. Long linear features (such as roads and tracks) were recorded in a separate vector line layer with unique numbers. Point, line, and polygon features were cross-referenced by their unique numbers where structures or lines were composed of multiple individual polygon features.

The archaeological features represented by point and line data were classified following a modified version of the method used by the Quarryscapes Project (Bloxam and Heldal 2008: 20-21), recorded in the attribute table of each point and line layer. This en-

Element	Feature Type	Feature Subtype
Resource	**Rock**	
	Commodity	
	Occurence	
Production	**Quarry morphology**	
	Quarry face	
	Quarry	Quarry
	Tool marks	
	Tools	
	Spoil	Spoil heap
	Work areas	Work areas
	Objects and object blanks	
Logistics	**Road**	Road
		Causeway
		Ramp
	Slipway	
	Track	Track
	Path	Footpath
	Stockpile	
	Harbours	
	Vehicle Track	Vehicle Track
	Stone feature	Cairn
		Alam
		Dam
	Carved feature	Petroglyph
Social infrastructure	**Stone built feature**	Windbreak
		Shelter
		Hut
		Hut (x room)
		Four poster
		Shrine
		Cairn
		Quarry P settlement
		Wall
	Ceramics	
	Epigraphics	
	Wells	Well
	Faunal/floral remains	
	Domestic artifacts	
	Blank Area	Tent circle

Table 1. Elements, feature types, and feature subtypes, used in the remote-survey. Quarryscapes categories (Bloxam and Heldal 2008: 20-21) are shown in bold and additions for the Hatnub Road remote-survey in normal type. Empty cells in the ‚Feature Subtype' column indicate that the Quarryscapes feature type was not used to date, but could be brought into use during subsequent phases.

sured that subsequent analysis was compatible with the Quarryscapes landscape characterisation in case of any future comparison. During the remote-survey it became necessary to make some additions to the Quarryscapes characterisation and add an additional 'Feature subtype' field to allow the remote-surveyor to make more specific observations about the shape of the structures and ensure all the information available in the satellite imagery was included in the attribute data. The hierarchy of 'Element', 'Feature Type', and 'Feature Subtype' categories used in the classification is shown in Table 1.

The attribute tables of the archaeological structures in the point and line layers also included an 'Uncertain' field, where the remote-surveyor recorded if they were uncertain about whether a feature was anthropogenic or natural. This system of data and attribute management made it possible to record all the information that was available in the satellite imagery in a flexible way that recognised uncertainty in the identification and interpretation of the features. All anthropogenic features visible in the satellite image were recorded using this system, except for clearly modern vehicular tracks.

Assessing the Accuracy of the Remote-Survey

To determine if remote-survey could substantially supplement or partially replace field survey it is necessary to determine how accurately it records anthropogenic features by comparing the features recorded in the satellite imagery to those present on the ground, a process known as 'ground-check' or 'ground-truthing' (Bubenzer and Bolton 2013; De Laet et al. 2015). This is an important part of the process of determining the accuracy of remote- survey in general and of the ongoing evolution of definitive method-

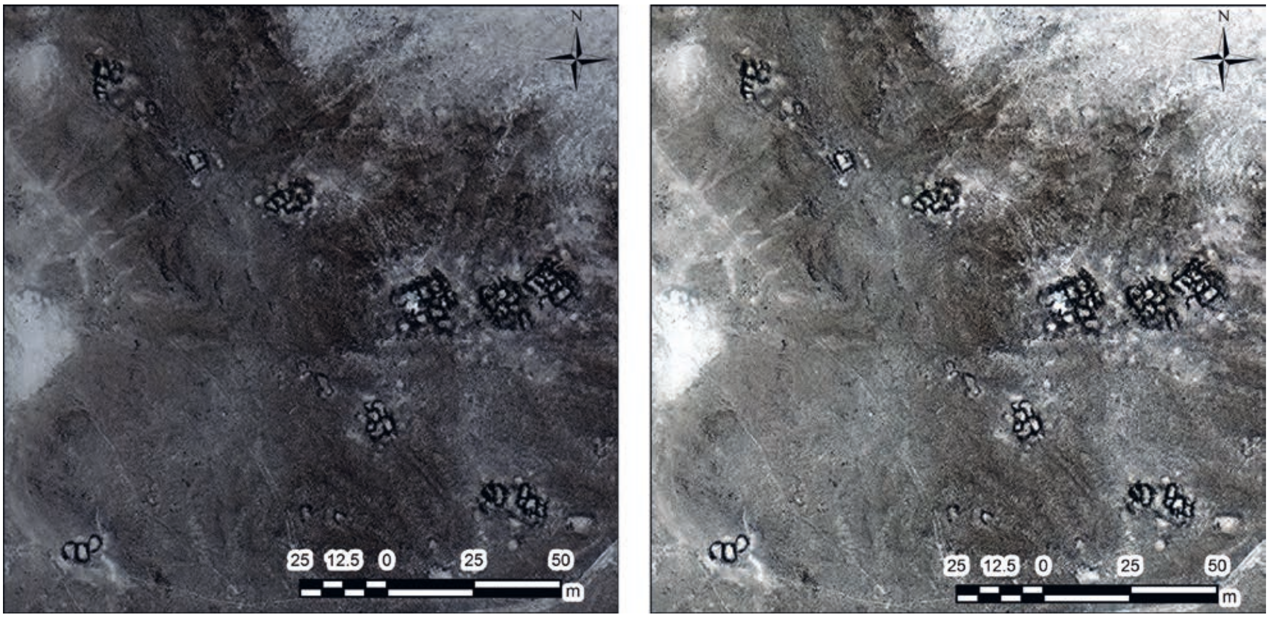


Figure 2. The effect of contrast stretching upon a darker area of the desert surface. Prior to contrast stretching (left) archaeological features are partly obscured. After contrast stretching (right) the archaeological features are clearly visible (Worldview-3 imagery © 2016 DigitalGlobe Inc supplied by European Space Imaging. Reproduced with permission).

ologies for archaeological remote-sensing (Parcak 2008: 67; Parcak 2009: 362).

In this project the accuracy of the remote-survey was assessed by comparison with extant data from Shaw's (2010) previous fieldwork on the site. To undertake this comparison Shaw's (2010: fig 3.1, fig 3.8, fig 3.12, fig 3.14, fig 3.16, fig 3.19, fig 3.21, fig 3.22 and fig 3.28) published plans were georeferenced and incorporated into the GIS as a layer. The archaeological features recorded in these plans were identified as far as possible in the remote-survey data and the feature numbers they had been given by Shaw were added to the attributes of the relevant points and lines in the remote-survey data. This made it possible to directly compare the results of the remote-survey with the field survey data and make an initial assessment of the accuracy of the remote-survey prior to further 'ground-truthing' fieldwork.

In accordance with current practices for assessing the accuracy of remote-sensing research (Dore and McElroy 2011: 16–17; Parcak 2007: 75), it was important to provide a numerical measure of the accuracy of the remote-survey when compared to the Shaw (2010) survey data. The results section includes the percentage of archaeological features recorded by the remote-survey that were also present in the Shaw (2010) survey data, as well as the percentages of false negatives (i.e., real archaeological features which were not found during the remote-survey) and false positives (i.e., features recorded in the remote survey which are not in fact archaeological). It should be noted that the calculation of false positives and negatives depends upon the accuracy of Shaw's fieldwork. It is possible that a feature recorded in the remote-survey will be classified here as a false positive if it was not recorded by Shaw (2010), only for subsequent ground-truthing to find that it is a real archaeological feature. This potential issue will be discussed further in the results section.

Results

This research project demonstrated that the method of remote-survey presented here is effective for the identification of small (greater than c. 1 m diameter) archaeological features across an open desert landscape, such as the Hatnub quarrying area. General observations on the method are presented below, followed by a direct comparison between the results of the remote-survey and an earlier on-site archaeological survey of 890 m^2 of the same landscape, undertaken by Shaw (2010) between 1985 and 1994.

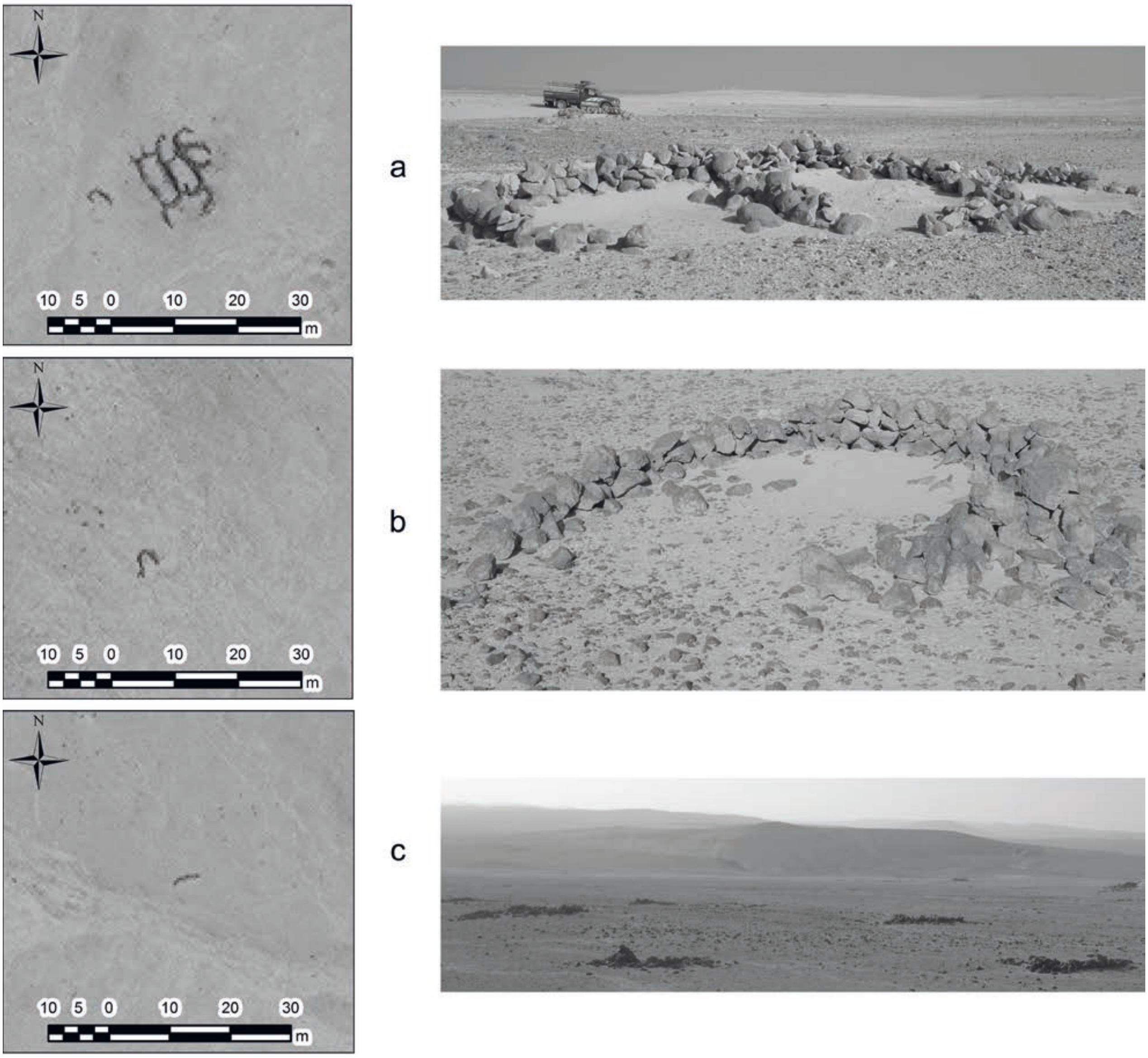


Figure 3. Types of habitations visible in the satellite imagery (left) and on the ground (right). (a) hut, (b) shelter, (c) windbreak (Worldview-3 imagery © 2016 DigitalGlobe Inc. supplied by European Space Imaging. Photos: Roland Enmarch. Reproduced with permission).

General Observations

The Hatnub desert surface is divided into two different types. In some areas weathering has eroded the natural limestone strata, leaving a dark stony surface that is known as 'hamada' in Arabic (Bubenzer and Bolton 2013: 71), interrupted by larger limestone outcrops. Other strata present a lighter surface colour and have a much softer, friable texture when exposed by weathering.

The initial review of the landscape using Google Earth imagery and subsequent analysis of the Worldview-3 image demonstrated that archaeological features appear clearly across both the dark and lighter parts of the desert surface because they inevitably present a discontinuity in it. Upstanding archaeological features are generally constructed from the dark weathered limestone pieces that cover the darker areas of the desert surface. They appear very clearly against the lighter-coloured areas and, despite being constructed of the same material, can be distinguished from the darker stony surface by the intensity of their colour and by drifts of lighter sand against the upstanding walls. Negative features (such

Feature subtype	Features	
	No	%
Huts	236	29
Shelters	244	30
Windbreaks	85	10
Blank areas	170	21
Cairns and alam	37	5
Road or track	20	2
Work area	9	1.1
Shrine	9	1.1
Spoil heap	3	0.4
Quarry	6	0.7
Wall	1	0.1
Total	820	100

Table 2. The 820 remotely-surveyed structures within Shaw's (2010) survey area, broken down by feature subtype.

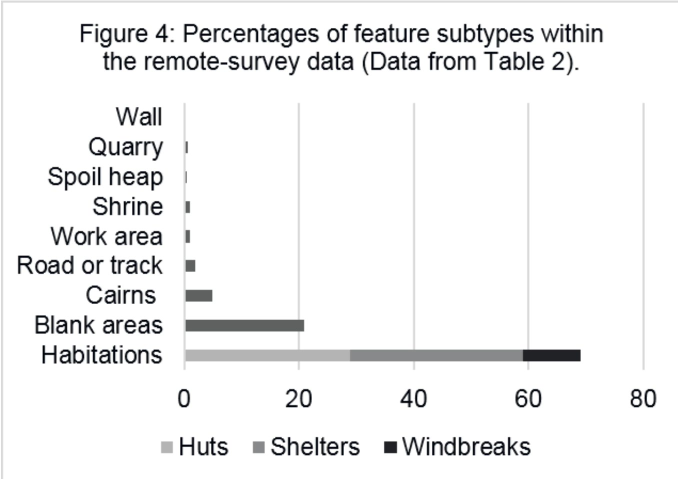


Figure 4: Percentages of feature subtypes within the remote-survey data (Data from Table 2).

	Structures	Roads, tracks, paths	Within destroyed 'Quarry P settlement south'	Total
Number recorded by Shaw	390	10	29	429
Number recorded by remote-survey	379	10	9	398
% of Shaw's features recorded by remote-survey	97	100	31	93

Table 3. Comparison of features recorded by Shaw (2010) and the remote-survey showing the percentage of Shaw's features that were accurately identified by the remote-survey.

as wells or pits) can be identified by the discontinuity they create in the desert surface and drifts of fine sand in the resulting depressions.

No additional enhancement was necessary beyond contrast stretching ('Lillesand, Kiefer, and Chipman, 2004: 492-499), which was also effective in the identification of Egyptian desert trails at Deir el Bersha (De Laet et al. 2015: 292). Figure 2 shows the effect of contrast stretching on the visibility of archaeological features in darker areas of the desert surface.

During his archaeological survey Shaw (2010: 40-48) noted that the habitations around Quarry P can be divided into three different types. The remote-survey revealed that these three types are also clearly visible in the satellite imagery (Figure 3):

a. 'Huts' include any feature with a full circuit of walls broken only by a small entrance, and any feature with more than one room. Where more than one room was present the number of rooms was recorded during the remote-survey.

b. 'Shelters' were less substantially built than 'huts' and were typically U-shaped. The central part of the U was usually lighter in colour than the surrounding desert, where stones had been cleared and sand had gathered. This assisted in distinguishing shelters from natural curving outcrops in the satellite imagery.

c. 'Windbreaks' were the most ephemeral of all, being little more than a single, slightly curving or sinuous low wall offering protection from the prevailing wind. Like the shelters the area inside the wall was usually lighter in colour than the surrounding desert.

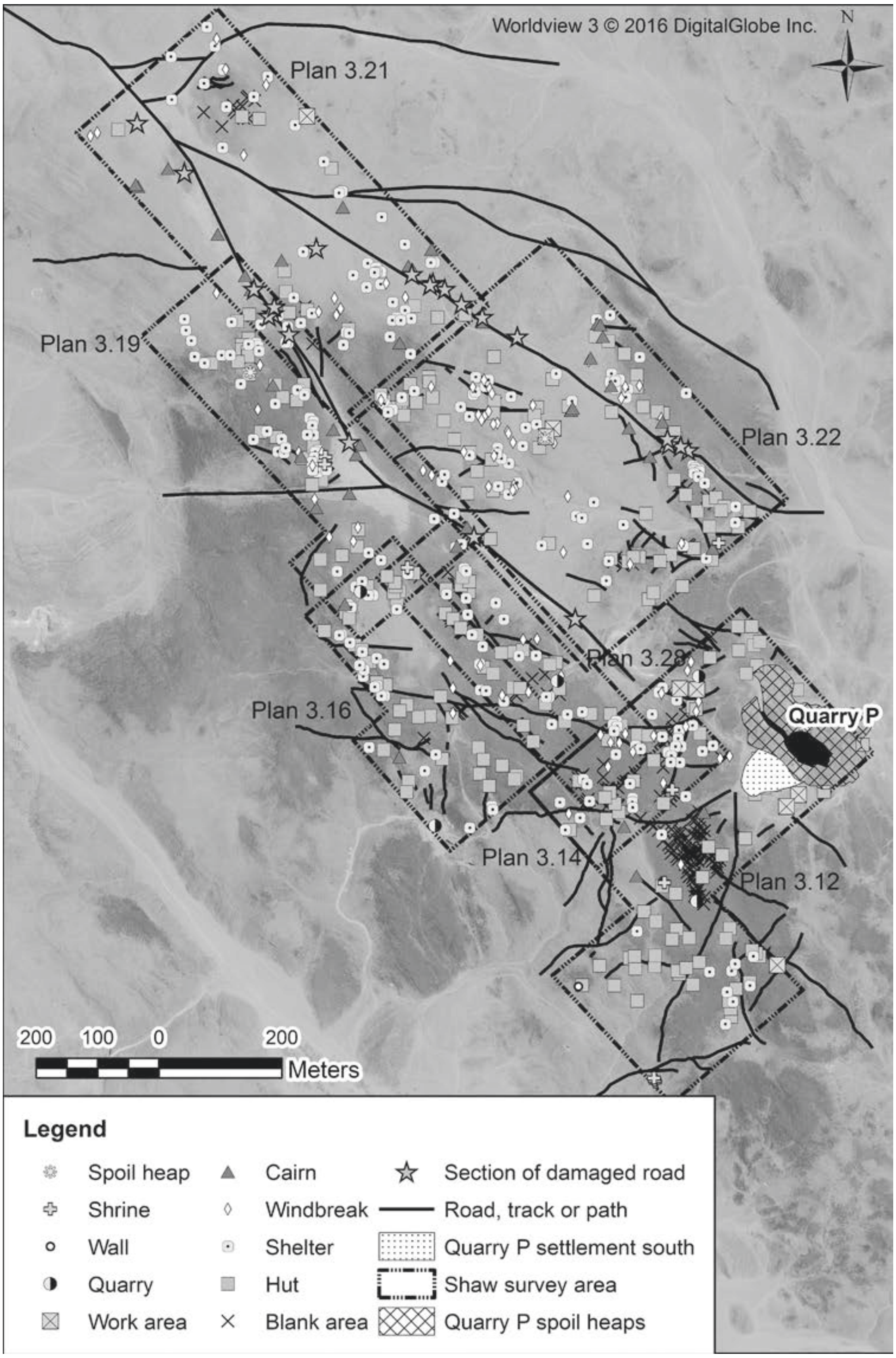


Figure 5. Distribution of archaeological features by feature subtype as recorded by the remote-survey, across the area originally surveyed by Shaw (2010) (Worldview-3 imagery © 2016 DigitalGlobe Inc. supplied by European Space Imaging. Reproduced with permission).

Comparison Between the Remote-Survey and Shaw's Survey Data

It took 20 days to prepare and remotely survey the 890 m^2 area originally surveyed by Shaw (2010) between 1985 and 1994. During these 20 days 820 structures and 125 roads, tracks, and paths were surveyed (Figure 4, Table 2, Figure 5).

To provide a numerical calculation of the accuracy of the remote-survey, the percentage of archaeological features found by the remote survey that were also present in the Shaw (2010) survey data was calculated, as well as the percentage of false negatives and false positives.

False Negatives in the Remote Survey | Table 3

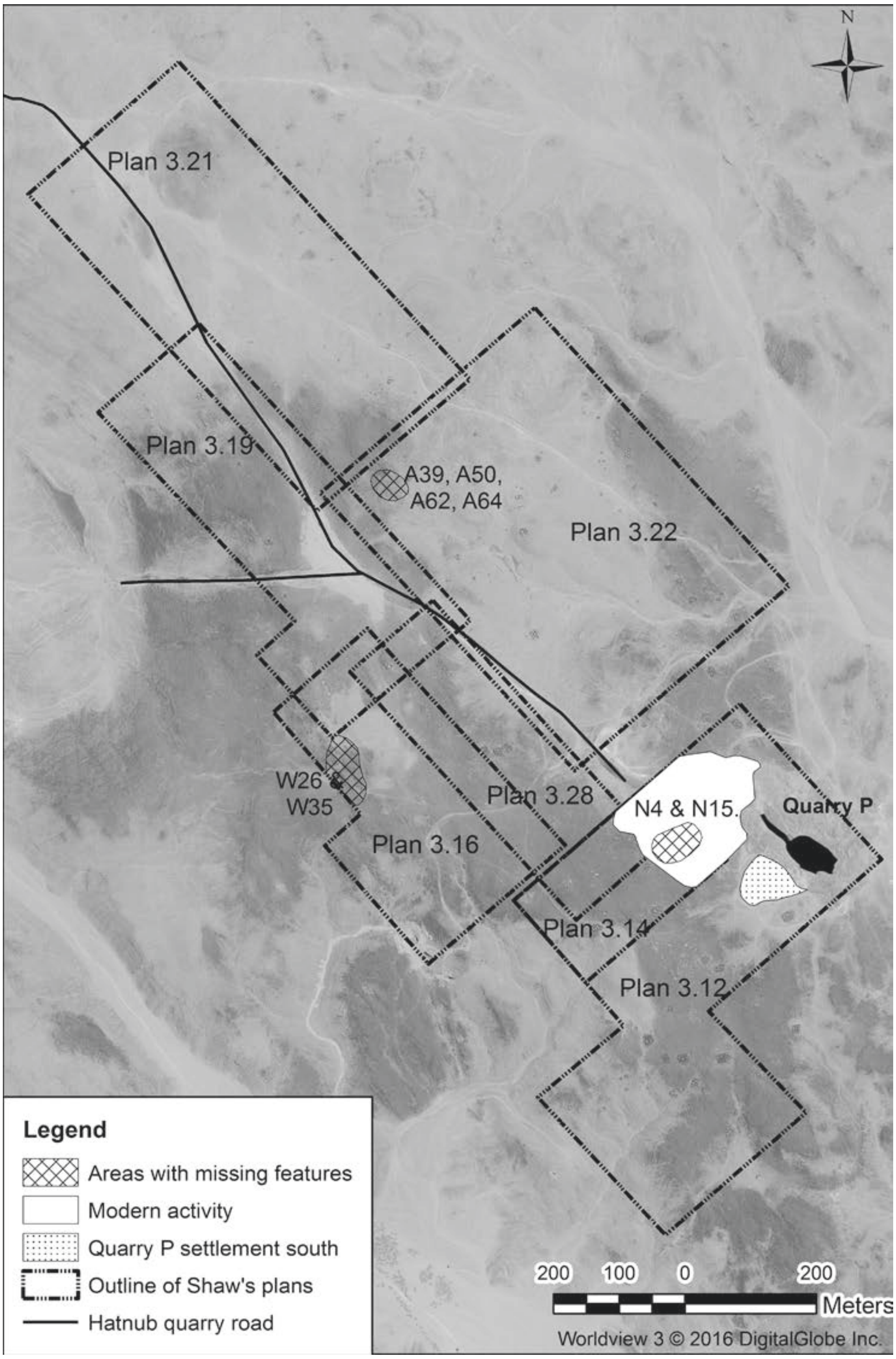


Figure 6. The area surveyed by Shaw (2010) showing where features recorded by him are missing from the remote-survey at the edges of his plans 3.22 and 3.16 and in the area of modern disturbance immediately west of Quarry P. (Worldview-3 imagery © 2016 DigitalGlobe Inc. supplied by European Space Imaging. Reproduced with permission).

compares the numbers of structures recorded by Shaw (2010) with the remote survey data to determine the efficacy of the remote-survey in identifying archaeological structures already known from Shaw's survey. Overall the remote-survey was very effective, finding 93% of the features recorded by Shaw and producing a very low number (7%) of false negatives.

The poorest result in terms of false negatives (features recorded by Shaw (2010) that were not located during the remote-survey) came from the dense concentration of settlement adjacent to the south side of Quarry P ('Quarry P settlement south' in Table 3 and Figure 6), where extensive modern activity around Quarry P has left this area almost entirely unintelligible since Shaw (2010) completed his research in 1994. If the 'Quarry P settlement south' is excluded from the data, the remote-survey produced false neg-

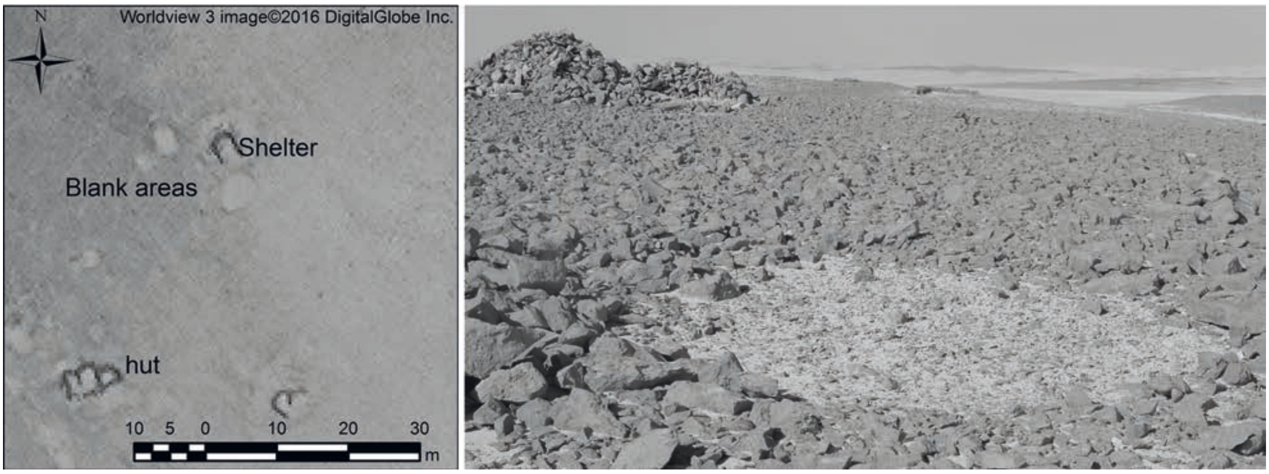


Figure 7. Blank areas' (left) as they appear in the Worldview-3 imagery and (right) on the ground (Worldview-3 imagery © 2016 DigitalGlobe Inc. supplied by European Space Imaging. Photo: Roland Enmarch. Reproduced with permission).

atives at a rate of only 3% across the rest of the area. A high proportion of the false negatives produced by the remote-survey are therefore the result of modern activity obscuring or destroying previously recorded archaeological remains.

Modern activity is probably also responsible for the absence of some other features (N4 and N15) from the remote-survey data. These features were recorded by Shaw (2010: fig 3.14) on the approach route immediately west of Quarry P, where the remote-survey found evidence of considerable modern activity.

Elsewhere the features in Shaw's survey which could not be located in the remote-survey tended to cluster in two areas at the edges of Shaw's field survey plans (Figure 6). Along the southwestern edge of the survey area it was difficult to relate Shaw's (2010: fig 3.16) plan to the satellite image and several features recorded by him (W26 and W35) could not be identified in the remote-survey data. Similarly in the centre west of the survey area on the edge of two plans (Shaw 2010: fig 3.21 and fig 3.22) several structures (A39, A50, A62 and A64) could not be identified in the remote-survey. As there is no evidence of modern destruction in these areas, it is difficult to determine why features recorded by Shaw do not appear in the satellite imagery. One possibility is that the records of the field survey are slightly less accurate at the edges of the plans. Alternatively genuine features might have been obscured in the satellite imagery. Only further fieldwork can determine if the features recorded by Shaw still exist and why they could not be found by the remote-survey. Despite these difficulties comparison of the remote-survey and Shaw field survey data reveals that the remote-survey produces a low number of false negatives and is almost as efficient as field survey at locating surviving archaeological features.

False Positives in the Remote Survey | The remote-survey recorded an additional 441 structures and 115 roads, tracks or paths that had not been identified by Shaw's (2010) fieldwork. The large number of additional roads and tracks recorded in the remote-survey is not a surprise since Shaw's plans only show the main quarry road, its spur to the southwest and very short paths approaching some of the shrines. There is no evidence that any other tracks, trails, or paths were recorded during Shaw's survey work. Confirmation of the archaeological nature of the additional 115 roads, tracks, and paths found by the remote-survey will therefore have to await further 'on site' ground-truthing.

Of the 441 additional archaeological structures recorded by the remote-survey but not by Shaw (2010), 21 are interpreted as modern features based on their highly rectilinear shape or superimposition upon areas of modern quarrying and disturbance. Most of these features have been constructed since Shaw's fieldwork was completed and would not have been recorded as ancient features by him even if they were in existence. Excluding the 21 modern features leaves 420 unexplained potentially ancient structures that were identified in the remote-survey but are not in Shaw's (2010) plans. These 420 features include 170 'Blank areas' (see Table 2). These areas were not

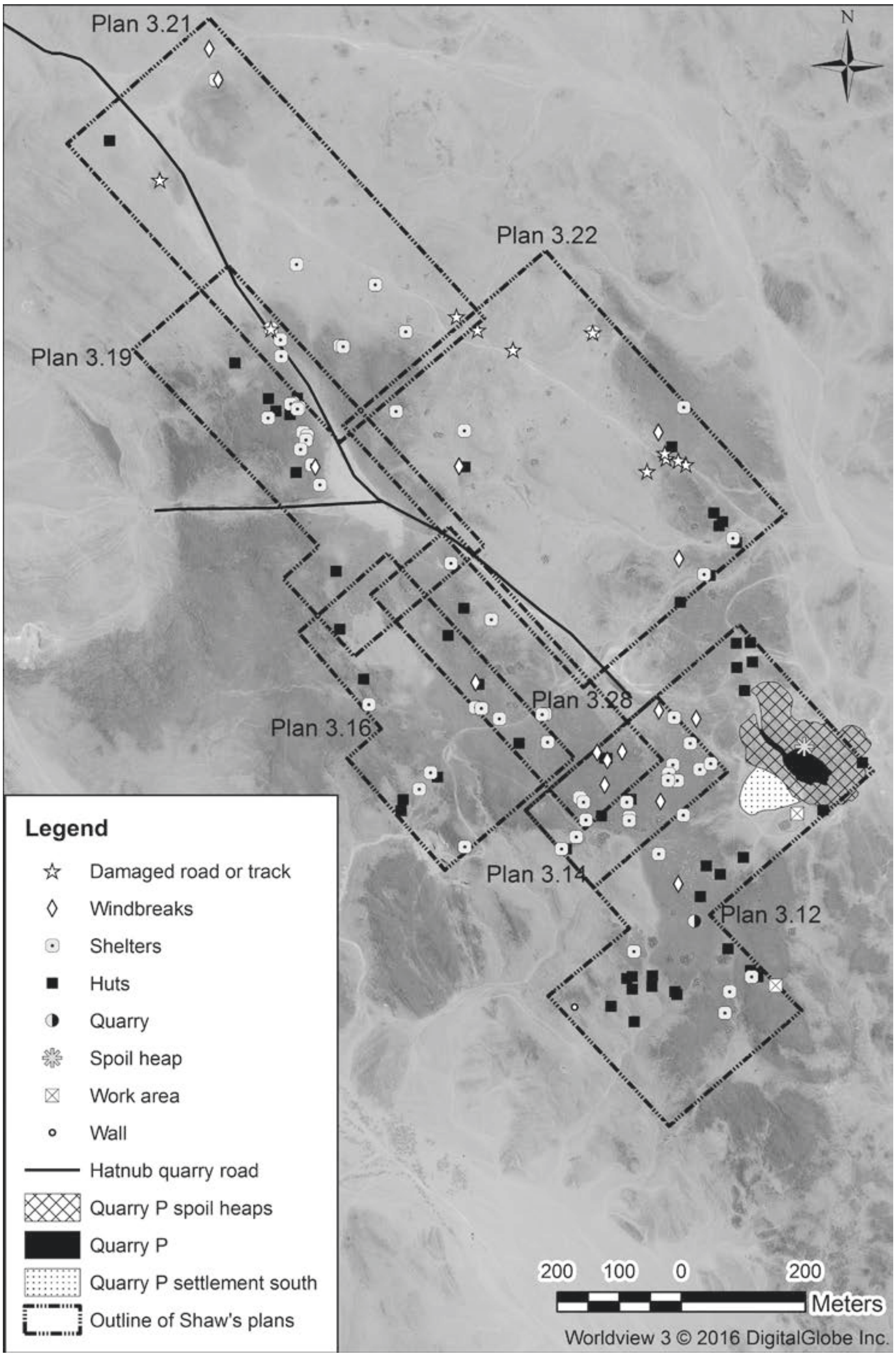


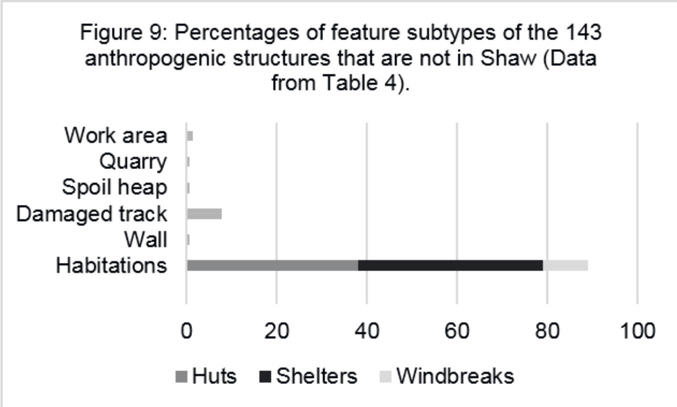
Figure 8. The 143 features classified as 'certainly' anthropogenic, but not in Shaw's survey data. Those around the edges and overlaps of Shaw's (2010) plans 3.16, 3.21, and 3.22 were probably missed by Shaw because of their peripheral location (Worldview-3 image © 2016 DigitalGlobe Inc. supplied by European Space Imaging. Reproduced with permission).

marked out by any specific walling, but appear as circular or sub-circular discontinuities in the stony surface of the desert (Figure 7). The most likely explanation for them is that they are small quarry pits filled with sand or 'tent circles' where the stones have been cleared from the surface to form a more comfortable space for a temporary shelter. Shaw (2010: 35) noted their existence but did not record them individually. The Blank areas were therefore excluded from the comparison with the Shaw survey data. This left 250 features in the remote-survey, which are of the types that Shaw recorded but are not present in his survey data. This is a high number of potentially false positives, representing 30% of the total structures recorded in the remote-survey.

The database shows that the remote-surveyor was reasonably certain that 143 of those 250 potential false positives were genuinely anthropogenic (Fig-

Feature subtype	Features	
	No	%
Huts	54	38
Shelters	58	41
Windbreaks	15	10
Wall	1	0.7
Damaged track	1	0.7
Spoil heap	11	1
Quarry	1	0.7
Work area	2	1.4
Total	143	100

Table 4. Breakdown of the feature subtypes of the 143 anthropogenic features that are not in Shaw's (2010) survey, but the remote-surveyor was certain were anthropogenic.



ure 8, Table 4 and Figure 9). As expected, the majority (127 or 89%) of these 143 structures were interpreted as habitations. This is consistent with both the remote-survey overall, where the majority (69%) of the structures were habitations of some sort, and with Shaw's (2010) survey data. Given the large size of some of the huts and the distinctive appearance of the other habitations recorded during the remote-survey (Figure 3), it is extremely unlikely that these 127 habitations are false positives. There is a faint possibility that some may have been constructed recently, but modern structures are generally identifiable by their square shape, thin walls (typically made with one layer of limestone bricks), and presence near modern quarries. Although final confirmation must await 'ground-truthing' fieldwork, it is likely that most, if not all of the 127 habitations are genuine archaeological features that were missed by Shaw.

Given the certainty with which the 143 anthropogenic structures were recorded by the remote-surveyor as genuine archaeological features, and the probability that many of them will be confirmed in 'ground-truthing' fieldwork, their absence from Shaw's (2010) data requires some explanation. Eleven of the 143 were located along the Hatnub quarry road and a secondary track to the north-east, and are probably either sections of these routes or nearby ancient structures broken up by modern traffic (Figure 8). Thus they may not have been visible as independent features when Shaw undertook his survey.

Figure 8 also shows that a number of the 143 features (including all the quarries and work areas as well as many habitations) cluster at the edges of Shaw's total survey area and along the edges of individual plans, particularly Shaw's (2010) plan 3.16, plan 3.21, and plan 3.22, and along the southern edge of plan 3.19. This suggests that the survey did not extend quite as far as these plans indicate and that archaeological features were missed at the intersection of survey plans, perhaps where one field season ended and another began. The distribution of habitations across Shaw's (2010) plans 3.12, 3.14, and in the centre of 3.19, is more difficult to explain, but these features may have been missed due to the practical difficulties of maintaining a consistent manual field survey over varied terrain. The identification of archaeological features in the remote-survey that were missed by field survey is consistent with the results of other remote-sensing surveys which undertook ground-truthing exercises (Dore and McElroy 2011: 16–17; Parcak 2007: 75). Further 'on-site' investigation of these features will confirm their anthropogenic nature and perhaps reveal why they were not included in Shaw's survey.

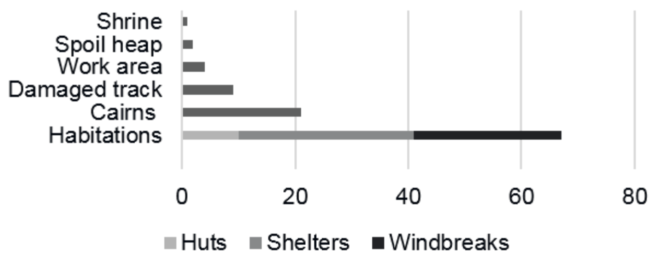
There are 107 structures in the remote-survey data where the surveyor was uncertain as to whether they were truly archaeological features or not (Table 5, Figure 10). Of all the structures recorded during the remote-survey, these 107 are the most likely to be false positives, as they are not recorded by Shaw (2010) and the remote-surveyor was uncertain if they were genuinely anthropogenic.

This group is dominated by possible habitations, which is consistent with the number of habitations in the remote-survey data and Shaw's (2010) field survey records. Normally habitations are easy to distinguish from the desert surface, but badly dam-

Feature subtype	Features No	%
Huts	10	9
Shelters	31	29
Windbreaks	26	24
Cairns	23	21
Damaged track	10	9
Work area	4	4
Spoil heap	2	2
Shrine	1	1
Total	107	100

Table 5. The 107 potentially false positives, by feature subtype. This table includes only those features that are not in Shaw's (2010) survey and where the remote-surveyor was uncertain as to whether they were truly anthropogenic or not.

Figure 10: Percentages of feature subtypes within the 107 potentially false positives (Data from Table 5).



aged or demolished habitations lose their distinctive appearance making them difficult to identify in the remote-survey. In almost all cases these features were classified as 'uncertain' because of the activity of modern traffic or quarrying that obscured their form or interrupted their distribution across the desert.

The only exceptions to this were the cairns and spoil heaps, which were often categorised as 'uncertain' because they appear as dark stony agglomerations on the desert surface, and look very similar to small natural outcrops, making them difficult to identify with certainty in the satellite imagery. Of all the features cairns and spoil heaps were the most likely to be categorised as 'uncertain', across the remote-survey area whether or not they were located in the area surveyed by Shaw (2010). Overall 70% of all cairns and 68% of all spoil heaps have been categorised as 'uncertain' to date. The difficulty of identifying these features emphasises the importance of the 'Uncertain' field in the remote-survey data. This field enabled questionable features to be recorded while ensuring the surveyor could express their doubts and flag the features for further fieldwork.

Given that Shaw (2010) did not record every single archaeological feature within his survey area, it is probable that some of the 107 uncertain features are genuinely ancient structures, but if they all proved to be false positives they represent 13% of the structures recorded within Shaw's survey area during the remote-survey. Some of these features will be targeted for 'ground-truthing' during the next phase of the project, together with other randomly sampled features elsewhere within the study area. Although some of these 107 features may prove to be genuine, prior to ground-truthing this figure of 107 or 13% is the best estimate for false positives within the remote-survey data.

Overall, and if corroborated in the field, the results presented above represent a substantial improvement over those recorded by Dore and McElroy (2011: 16) where analysis of satellite imagery only found 92 of 157 trail segments, giving a rate of 59% for false negatives. The Hatnub remote-survey results (with false negatives at 7% and false positives estimated at 13%) are more comparable to Parcak's (2007: 72-74) identification of Egyptian tells (settlement mounds) from multi-spectral imagery, which exhibited a rate of 2% false negatives and no false positives in Middle Egypt, and 2% false negatives and 10% false positives in the Egyptian Delta. De Laet et al. (2015) and Bubenzer and Bolton (2013) do not provide statistics on the numbers of false positives or false negatives in their research, although the trails they recorded were checked during fieldwork.

Conclusion

Overall, this research found that remote-survey of desert landscapes is a viable means of accurately and rapidly recording small diffuse features across a large landscape. Archaeological features of 1 m in diameter or larger were consistently visible in the satellite imagery despite variations in the natural surface of the desert and the type of archaeological feature. The imagery was sufficiently clear to enable the remote-surveyor to locate the different types of windbreaks, shelters, and huts. Although the speed of any survey is naturally dependent upon the number of archaeological features present, the remote-survey was clearly substantially quicker than the original fieldwork and also required little cost beyond the price of the imagery (£2000) and the software. The geolocational accuracy of the Worldview-3 image used in the remote-survey ensured that the resulting plan of archaeological features is as precisely and accurately located as is currently possible, which is critical for subsequent ground-truthing.

Comparison between Shaw's (2010) field survey data and the remote-survey demonstrates, even before ground-truthing fieldwork, that the latter is reasonably accurate and has a level of accuracy that compares well with that found during other projects. The remote-survey data has a low rate (7%) of false negatives, indicating that it is almost as efficient as field survey at identifying known archaeological features. Detailed examination of the survey data revealed that the false negatives were mostly the result of recent damage to archaeological features previously recorded by Shaw, which rendered them incomprehensible during the remote-survey. When the severely damaged Quarry P settlement south was excluded from the analysis, the rate of false negatives decreased to 3%.

Although the data initially indicated an alarmingly high number (441 or 54%) of potential false positives in the remote-survey, careful examination of the methodology employed by Shaw and the remote-survey revealed that some of this was due to different methodological approaches, particularly in recording the 'Blank areas'. After these differences had been eliminated, 250 remote-survey features remained unidentified in Shaw's survey data, indicating that up to 30% of the remotely surveyed features could be false positives. Given that the remote-surveyor was certain that 143 of these features were anthropogenic, it is likely that the true rate of false positives is much closer to the 13% (107) of structures where the surveyor could not be certain of their human origin.

Final confirmation of the accuracy of the remote-survey across the whole 100 km2 survey area awaits further 'ground-truthing' fieldwork in the near future, but this paper has demonstrated that high resolution satellite remote-sensing is a suitable method for generating an initial plan of small, diffuse archaeological features dispersed across a large area of varied desert terrain and can supplement or partially replace on-site archaeological field survey in desert landscapes.

Undertaking remote-survey prior to fieldwork at Hatnub will reduce the amount of time and resources required to record the archaeological landscape and ensure that fieldwork is targeted at uncertain or interesting structures. The creation of the remote-survey plan will also facilitate future fieldwork on a practical level. Using mobile-GIS technology the satellite imagery and remote-survey plan will be combined with GPS-enabled tablet-based recording devices to provide the maximum information during field survey and enable modifications to the data to be made directly. This will facilitate rapid data collection and eliminate the need to obtain and transport large survey equipment to the site, with a concomitant saving in time and resources.

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Testing the 'Small-Site' Approach with Multivariate Activity and Network Analysis

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Abstract

A.L. Kroeber's 'small-site approach, which posits that small-scale sites can be used as touchstones for understanding materials observed at large-scale centers was never properly tested on Peru's north coast. While fundamentally sound with modifications, the original approach was limited by the inadequacy of computational tools to effectively study differing relationships between materials and activities observed in and/or absent from archaeological settings of differing scale. Although regional settlement pattern survey and the analysis of large-scale monumental centers have long been the popular means of archaeological investigation and cultural assessment in Peru, the complementary investigation of smaller-scale quotidian spaces and households is largely lacking. Combining activity and network analysis to identify differential relationships observed in well studied small-scale (Cojal) and nearby, contemporaneous, large-scale (Pampa Grande) household contexts, this paper tests the adequacy of the small-site approach for elucidating patterns that characterize complex social interrelationships.

Keywords: small-site approach, activity analysis, network analysis

Introduction

Working during an era when archaeologists were primarily concerned with the construction of trait-based artifact typologies and the definition of culture areas based on artifact assemblages and distribution, Alfred L. Kroeber put forth a brief statement on the methods of Peruvian Archaeology in which he recognized that "the matter of associations is not only fundamental in archaeological methods, but so simple as sometimes to be taken implicitly, or even overlooked" (Kroeber 1963: 64). In 1942, in an address to the Faculty of Letters of the University of San Marcos in Lima, Kroeber delivered his only general statement concerning his views on archaeological method and theory, discussing the "significance of differential associations, stratigraphy, seriation, and the advantages of studying small sites to establish units of contemporaneity before attempting to sort out the sequence of occupation at large sites" (see introduction by Rowe in Kroeber 1963). While working under the same Culture History paradigms as his contemporaries, and with some untenable assumptions concerning stratigraphy and seriation, Kroeber's small-site approach constitutes an early effort to address relational characteristics of archaeological sites of differing scales and complexity (e.g., small and large sites). Although his approach was never given appropriate consideration nor effectively tested on Peru's north coast, it remains one of few materially-oriented interaction models developed for Northern Coastal Peru.

Kroeber was the first scholar working in the Central Andes to suggest the advantages of studying small archaeological sites. Based on his careful survey and documentation of archaeological materials he observed, he presumed that because small sites possess a more restricted range of components and are likely to be more ephemeral than their large-scale counterparts, small sites present the opportunity to examine phenomena that remain relatively unaltered by long-term occupation and interactivity. Speaking of the value of small site studies in the context of the ceramic objects they possess, Kroeber (1963) hypothesized that materials obtained from small sites can be used "...as a touchstone to segregate out the phases occurring within the material obtained from larger sites, whose populations may have been ethnically mixed or may have had wide relations to commerce, or… persisted through several stages of changing culture". Foundationally, he defined his approach as the study of the "small site of pure style; namely the ruins, rubbish or cemetery left by a small population occupying a given site for a relatively short period" (Kroeber 1963:70). Although Kroeber adopted the antiquated assumption that pure cultural forms exist and never properly defined constituents (beyond pottery styles) of small or large sites, the small-site approach provides a valuable alternative to politically-situated Peer Polity (Levy and Shalev 1989; Renfrew and Cherry 1986), or economically-grounded Core-Periphery (Frankenstein and Rowlands 1978) models for exploring relationships among archaeological sites and broader social spheres. In the present work, I explore evidence of multicrafting activities (pottery manufacture, metalsmithing and stone working) as a means by which to expose relationships shared by the major urban site of Pampa Grande and mid-scale site of Songoy-Cojal (Figure 1). In the small coastal valleys of North Coast in particular, small hamlets and villages dominate the prehispanic landscape of the first millennium making the small-site approach an important addition to the household and settlement pattern study repertoire.

For example, the study of households (or houses) is seen as an access point for understanding meaningful components of persistent social institutions (Deetz 1982; Kent 1984; Kent 1990; Nash 2009; Rapoport 1969; Rapoport 1990; Tringham 1995; see Aldenderfer 1993). While the importance of household craft production is now well established (e.g., Ames 1995; Costin 1991; Costin 2001; Feinman 1999), the study of household spatial organization is generally regarded as a better indicator of cultural differences or change, than house form or exterior alone (Hegmon 1998; see also Stanish 1989; Wilk and Rathje 1982). A critical point of concern in the Andes, however, is that houses are excavated as "homogenous containers" from which the sampling of individual parts is considered to provide sufficient data to evaluate relative differences among institutions (e.g., economy, exchange, production, diet, etc.). Although embedded in the small-site approach, as I illustrate below, household approaches lack "viable models that link house remains to lived communities, polities, and multipolity spheres of interaction" (Nash 2009:208).

At broader regional levels, the valley-wide "saturation technique" implemented by the Virú Valley project members during the 1940s remains a primary method of archaeological investigation in the Andes (Schaedel and Shimada 1982). This approach, however, suffers from the same general inability to understand relationships within and between sites, particularly those in different valleys or regions. Although originally aimed at understanding "all aspects of man's culture in a single valley" including architectural, occupational and community development patterns, as well as prehistoric religious, social, and political structures (Willey 1953), the foundational assumption that a single well studied valley could be understood as a microcosm of the entire Central Andes (Schaedel and Shimada 1982:360-61) has had a sorely homogenizing effect upon our understand of relationships between and among sites of differing scale and complexity. The widely held view of dominant and homogenous socio-political entities that persists in both household and settlement pattern studies, for example, is the result of long-standing major emphasis placed upon the study of highly visible art styles, monumental constructions and major archaeological sites (Shimada 2010). Although widely accepted settlement pattern studies presume that individual settlements and central places form an integrated whole (Kowalewski 2008), the approach overlooks the strength, weakness or types of relationships such entities might possess. Despite Kroeber's similar view that civilizations (and their material remains) were aesthetic and ideological wholes – consisting of the forms or patterns of the arts, government, law, social relations – he placed emphasis upon the differential relationships that existed among sites and civilizations that occupied them (Kushner 1969).

Speaking on the coexistence of objects or qualities which occur together on the ground, Kroeber

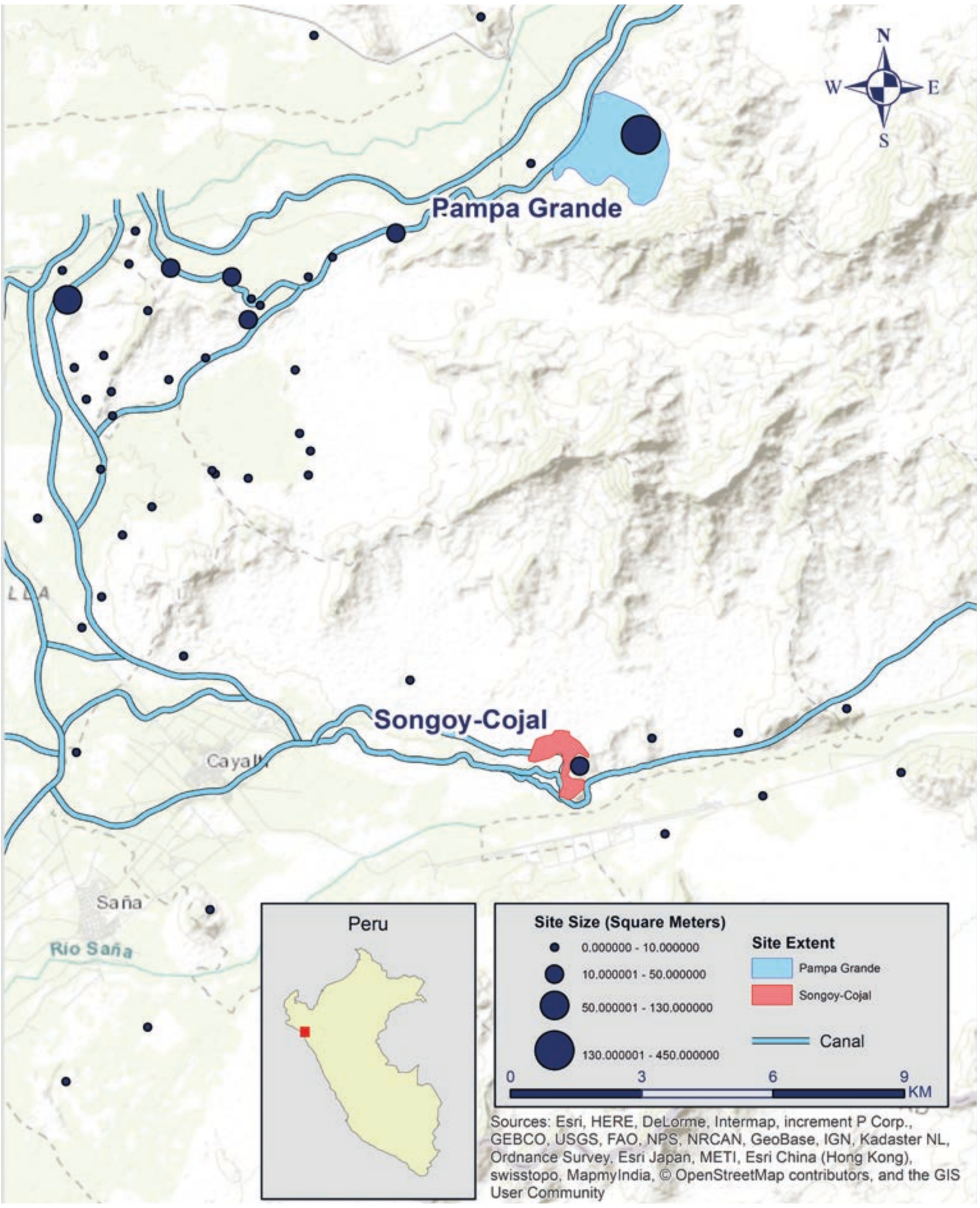

Figure 1. Regional map showing sites mentioned in the text, their extent, and relative size of these and other sites known in the Lambayeque-Zaña intervalley zone, North Coast, Peru.

emphasized the notion of interrelated part-to-part or part-to-whole (small-to-large site) relationships, proposing three testable hypotheses concerning relationships between and among north coast settlements:

> …if two classes of objects, or features of style, or other phenomena of the past, both occur repeatedly, but never in association, their very dissociation is also an objective, scientific fact, although a negative one. At times, the situation is less regular, in that phenomena A and B may occur either separately or in association; or A may associate with C, and B with C, but never A directly with B alone. In such a case, we are manifestly confronted with a partial correlation. A and B are manifestations mainly distinct in their geography or history, but also contiguous or overlapping; or, they both overlap with C. The associations, and dissociations, attain their full reliability only when they are determined with sufficient fineness [Kroeber 1963:64-65].

As illustrated below (Figure 2), the small-site approach produces a model that differs from Peer Polity and Core-Periphery models in terms of the emphasis placed upon interrelationships between and among sites. Although focusing on pottery style as a primary line of data, Kroeber's approach is expandable to

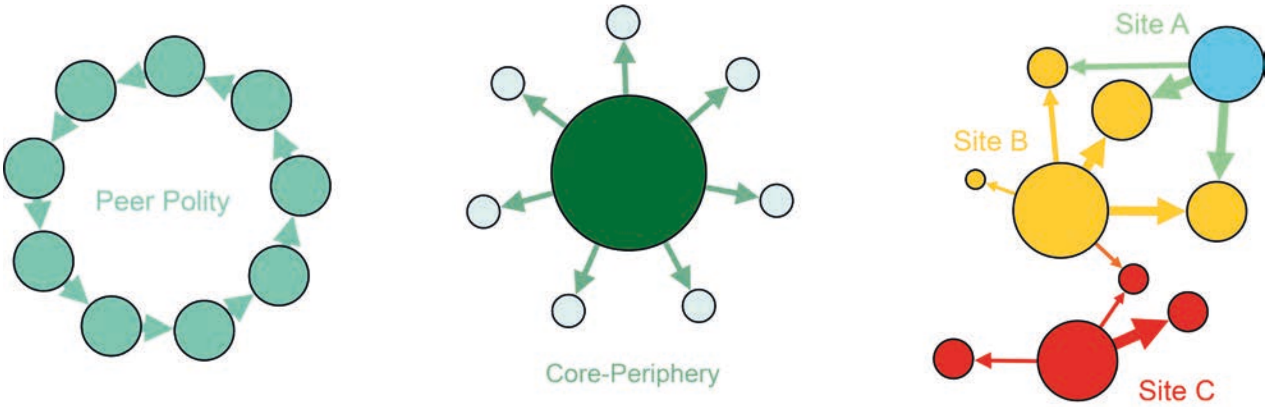

Figure 2. Generalized graphs depicting Peer Polity, Core-Periphery and Kroeber's Small-Site models side-by-side.

other lines of data. The foundational assumption is simply that the study of the more limited range of materials available from small sites, should reveal important relationships when compared to other entities.

Although relatively more complex when visualized as a network, Kroeber's model relies on only a few foundational assumptions that are applicable to a broader range of materials and social settings (see Moseley and Mackey 1972). Importantly, however, neither Kroeber nor Moseley-Mackey provided an operational definition of a "small site" or "large site". The current work sees this distinction as one of both size and complexity, small sites being generally less spatially extensive and internally complex than their large-site counterparts. Given this broad definition, the small-site approach provides an appropriate framework upon which to test the kind and strength of links that tie micro-scale household settings to macro-scale urban, religious or political centers that have long been ignored in the Andes.

Despite various assumptions and perspectives that are no longer tenable (as addressed previously), however, the main factor that undermined the testing of the small-site approach was the inadequacy of computational tools to effectively study the degree and kind of relationships that certain combinations of objects or materials imply. The recent popularity of studying social networks throughout the social sciences and in archaeology in particular (Peeples and Roberts 2013), combined with the availability of popular opensource software such as UCINET and Netdraw (Borgatti 2002; Borgatti, Everett and Freeman 2002) or PAST (Hammer, Harper and Ryan 2001) or Gephi (Bastian, Heymann and Jacomy 2009), now renders the exploration of Kroeber's model both feasible and accessible.

Using SNA to Test Kroeber's Model

The analysis of networks has long been a principal line of inquiry in archaeological investigations which aim to elucidate "patterns and processes of interaction in past societies" (Knappett 2013a:3). The effectiveness of applying social network analysis (or SNA) techniques as a concrete and quantitative means by which to test relationships among a wide variety of archaeological phenomena is now becoming more widely recognized; increasingly, archaeologists have begun to apply formal SNA approaches that are based on well-established models that have developed in the broader social sciences (see Borgatti et al. 2009 ; Brughmans 2013; Peeples and Roberts 2013 for excellent overviews). While formal conceptual and methodological models for studying various types of social networks emerged outside archaeology (Carrington, Scott and Wasserman 2005; Wasserman and Faust 1994; Scott and Carrington 2011), such techniques have effectively been applied in the context of regional interaction studies in archaeology (Knappett 2011; Knappett 2013b). As a number of recent archaeological applications effectively demonstrate, SNA is adaptable and useful to archaeologists on many levels, from the exploration of broad social, political and economic spheres at macro-regional scales when combined with GIS (Golitko et al. 2012; Mills et al. 2013b; Mills et al. 2013a; Rivers, Knappett and Evans 2013), to identify network connections at the micro-scale when combined with ethnographic data and material culture (Mol and Mans 2013) and even in the development of agent-based computer models to understand past conceptualizations of space and explore the dynamics of information diffusion (Graham 2006). An area of research not widely studied but highly amenable to techniques used in SNA, is household-level craft production, a topic of considerable interest in my current research and of broader applicability in archaeological applications of SNA for micro-level archaeological analyses as well.

Importantly, networks have formal properties (nodes and links) that are essential for discerning how various types of phenomena are related (see Knappett 2013). In this regard, networks are not simply a metaphor for human interaction, but a precise mathematical construction used to represent, analyze, and model interactions (Phillips 2011). While not all archaeological data or methods apply, there are important advantages to SNA, including the emphasis placed upon relationships (links or ties) among archaeological phenomena rather than the study of the phenomena (i.e., sites) themselves, and the formal methods available for characterizing different kinds of networks (Mills et al. 2013b). In addition to nodes and links, concepts such as network centrality – for which a variety of measures (e.g., degree, betweenness or eigenvector centrality) have been defined (see Peeples and Roberts, 2013:3005 for an excellent summary of various centrality measures useful for archaeological network analyses) – provide measures for understanding a given node's position and importance within a social network. Despite some limitations and assumptions that are now untenable in the original form, what makes Kroeber's small-site approach useful is its local yet expandable focus (i.e., the exploration of how small-to-large site relationships might be understood and the accompanying model from which to depart).

Constructing the Network

While it is important to recognize that similar material configurations may indicate different practices in different social settings, or conversely, that similar practices may result in different material configurations at different social levels (e.g., pottery manufactured for trade or external consumption vs. personal items), and that some practices carried out in large-scale settings (e.g., ceremonies or feasting) may have been carried out quite differently at smaller scales (Shimada 1978; Shimada 2007), the investigation of how such relationships might be quantified and the degree to which certain kinds of relationships manifest, finds its place in SNA. In the present case, I focus upon household craft production activities as a way to test relationships among materials recovered from highly differentiated yet contemporaneous household contexts in both small- and large-scale settings. As mentioned above, while the importance of household craft production is a topic of much interest, the relationship between different types of craft production activities, or multicrafting activities conducted outside formal workshop settings remains poorly understood.

To better understand these relationships, I began with the construction of a simple binary affiliation network matrix (after Wasserman and Faust 1994). Archaeological compounds included in this analysis, along with associated craft-related materials that were recorded and/or recovered during surface surveys and excavations of household contexts at the north coast sites of Pampa Grande and Cojal. While the extremely large-scale urban metropolis known as Pampa Grande has been extensively and intensively studied and excavated over the past few decades, the archaeological site of Cojal consists of only a few architectural compounds, three of which were partially excavated during my recent fieldwork at the site of Cojal. Materials considered in the present work are limited to those most diagnostic of three (possibly four) very different craft activities: stone/shell pendant manufacture, pottery manufacturing, and metalworking/metallurgy. In the examples in Table 1 and Figure 3, combined evidence of each activity (or activity-related set of attributes) and archaeological context from it was recovered is shown as a binary matrix where "1" represents a positive find in a particular context (and thus membership in a craft activity), and "0" represents a negative find (or absence from a given context).

As Peeples and Roberts (2013) have recently addressed, the use of simple binary networks for exploring relationships in archaeological cases is not particularly illuminating nor does it produce data that yield straightforward results. Although the construction of the binary affiliation network matrix was

Architectural compound	Pottery mold	Overfired pottery	Polishing stone	Possible blow tube	Copper ore	Crucible (fragment)	Prills	Metal finishing tool	Grinder bowl	Grinding/ pounding stone	Ash	Heavily burnt soil	Stone pendant preform	Stone pendant
	C1	C2	C3	M1	M2	M3	M4	M5	P1	P2	P3	P4	S1	S2
CA#1	1	0	1	0	0	0	0	0	1	1	0	0	0	0
CA#3	1	0	1	1	1	1	1	1	1	1	1	1	1	1
CA#4	0	0	1	1	1	1	1	0	1	1	1	1	1	1
CA#6	1	1	0	0	0	0	0	0	0	0	0	0	0	0
CA#7	0	1	0	0	0	0	0	0	0	1	1	1	0	0
H38	0	0	0	0	0	0	0	0	0	1	1	1	0	0
TALM	0	0	0	0	0	0	0	1	0	1	1	1	0	0
D47Z	0	0	0	0	0	0	0	1	0	0	1	0	0	0
D47Y	1	0	1	0	0	0	0	0	0	0	1	1	0	0
D36O	0	0	0	0	0	0	0	1	0	1	1	0	0	0
H11	0	0	0	0	0	0	0	0	0	0	0	0	0	0
D47X	0	0	0	0	0	0	0	0	0	0	0	0	0	0
DR	0	0	0	0	0	0	0	1	0	0	0	0	0	0

Table 1. Binary affiliation network matrix between architectural compounds and craft-related variables.

useful for identifying broad linkages between 'like' materials observed in various contexts at each of the sites studied, additional steps are necessary.

While the materials included in this study have been classified by presumed functional characteristics, the relationships among the various lines of data have important implications for how multicrafting activities and other archaeological phenomena might be better understood not only through the analysis of smaller-scale sites, but also in terms of the interrelationships among crafting institutions themselves. The attributes considered combine various lines of evidence (C-ceramic manufacturing items and byproducts, M-metallurgical and metalworking tools and byproducts, P-general processing tools or byproducts, S-stone pendant manufacturing and byproducts) considered relevant (or potentially so) for carrying out crafting activities. When grouped and weighted categorically, the various lines of information reveal important ties that were not immediately visible in the binary graph above.

The new categorical groups craft production related variables were weighted independently using Jaccard's coefficient, and then visualized according to those ties, rather than ties between individual variables as in the preceding graph. Using the similarity coefficient as a measure of the strength of ties between archaeological contexts for each category of information, it was possible to explore and distinguish among the types of relationships they share. Figures 4a, b, c and d below show the strength of various categorical relationships across the study areas.

I then re-combined the grouped craft production categorical variables, now weighted by their similarity indices, to explore the overall of strength of ties among the craft-related data, using a simple measure of degree centrality, defined as the sum of weights for each node's ties to all others (e.g., Opsahl, Agneessens and Skvoretz 2010), in this case, the ties among architectural compounds for each of the four groupings of craft production evidence which were then used to generate a graphical map depicting the relationships across architectural compounds at both sites (Figure 5). Here, it is possible to identify the relative importance or prominence of various architectural compounds (e.g., in terms of the craft production activities carried within them, as well as to identify precisely which practices (pottery manufac-

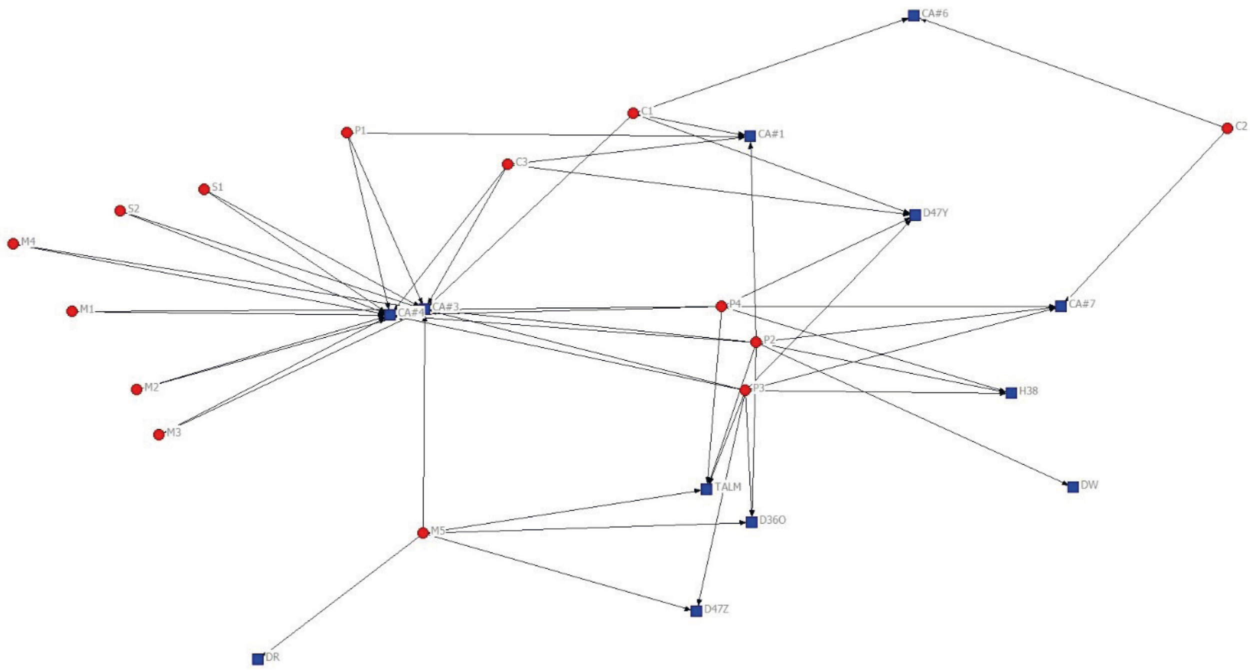

Figure 3. NetDraw (Borgatti 2002) graph based on the network affiliation matrix.

ture, metal crafting and stone working) were shared across small- and large-site boundaries.

Small-Site Approach Operationalized

Through the implementation of the SNA approach to test Kroeber's foundational ideas, it was possible to identify and expose various relationships that were not previously accounted for and or previously studied at the sites of interest. Initially, the distinctive shape of the binary graph is intriguing, given the nature and location of first order ties relating evidence of practical crafting activities to associated archaeological contexts. At first inspection, the binary graph appears to suggest the highly distinctive character of the two sites under study. However, when visualized in the weighted graph series it is possible to readily identify where and how linkages are reflected in the data.

While the fundamental link (or ties) between ceramic production materials across the sites and compounds was generally expected, the strength (or weakness) of certain crafting linkages across the two sites, was not. The relatively stronger ties for processing materials, suggests that crafting practices were carried using similar tools and in similar ways at both sites. This has broader implications for understanding the nature of relationships between craft producers, patrons and consumers living or working in the study areas. In this regard, the applicability of SNA techniques for studying even micro-scale archaeological data has much potential for future research in the context of craft, or multicraft production studies, and for other types of micro-scale archaeological research as well.

Perhaps the most valuable potential of the small-site approach is found in its ability to resituate focus away from poorly integrated studies of individual houses or regional settlement patterns. By focusing on the relationships between communities and their practices (Meyerhoff and Strycharz 2013; Wenger 1998), through the study of small and large sites (or areas of sites) it is possible to tightly integrate datasets of different size and complexity. While this test case illustrates the utility of SNA to test ideas and proposals concerning relationships between sites, it is expandable and of potential utility for addressing a broader range of sites and regions and produce higher-resolution picture of the past than that emerging through household or regional settlement pattern studies alone. While certain relationships exposed in the current test case are not unexpected, the ability to detect differential relationship among various datasets between sites and among contexts is most appealing.

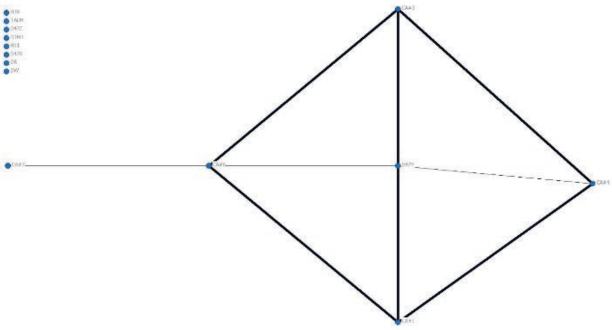

Figure 4a. Pottery Crafting Evidence (C category)

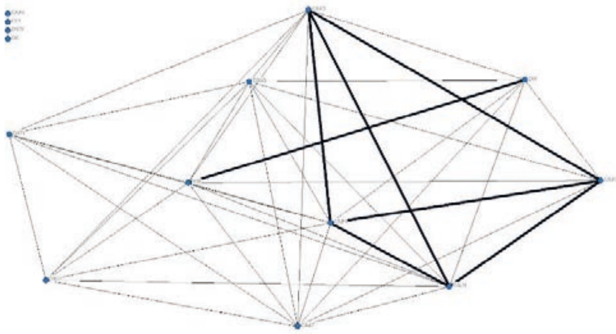

Figure 4c. Processing Evidence (P category)

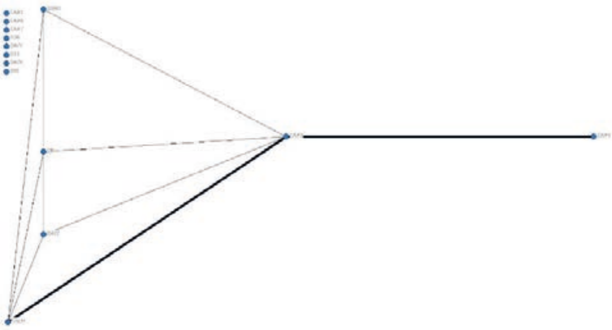

Figure 4b. Metal Crafting Evidence (M category)

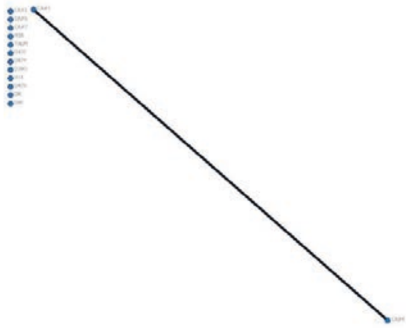

Figure 4d. Stone Working Evidence (S category)

Figures 4a, b, c and d. Network visualizations of the contextual relationships between (a) ceramic, (b) metal, and (c) stone craft production materials categories, and related (d) processing materials using NetDraw (Borgatti 2002).

Concluding Remarks

With several important refinements to the aims of Kroeber's Small-Site approach and by implementing formal techniques from social network analysis, or SNA, it was possible to effectively implement and test foundational ideas he proposed nearly a century. In this application of SNA, it was possible to expand beyond the original scope of the original method. This ability to explore the range of social contexts in which object and materials exist archaeologically has important implications for understanding social interrelationships (in the absence of written or other documented records) that existed nearly a millennium ago on Peru's north coast. While household studies are in critical need of expansion in the Andes, the future of these works lies in the ability to systematically understand relationships among micro-scale settings and broader macro-regions, which is currently limited by the inability to link the two together. With its power to resolve uncertainties concerning the relationship between household and settlement patterns studies, and to pinpoint the locus of differential, rather that direct part-to-whole relationships, Kroeber's small-site approach, presents the opportunity to effectively strategize the study of many types of social relationships between archaeological sites of differing scale and complexity using formalized techniques derived from SNA.

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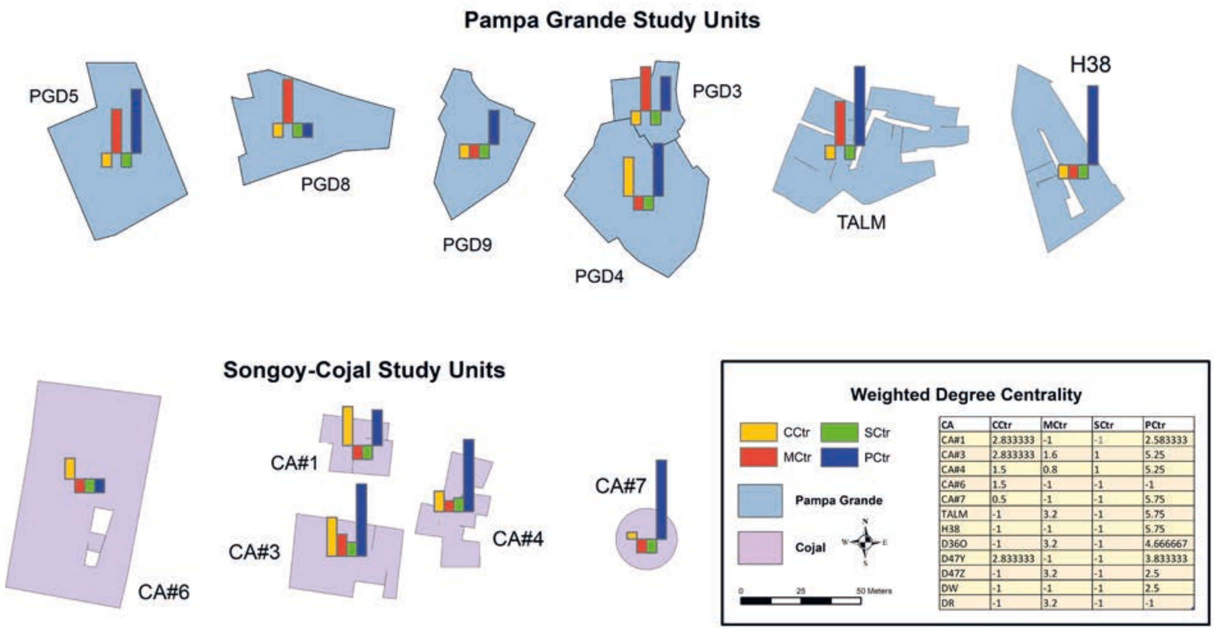

Figure 5. Study unit plan maps indicating prominence of craft-producing nodes based on weighted degree centrality measure. Longer bars indicate the potential for shared relationships in different archaeological contexts and different archaeological sites.

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Context as Theory: Towards Unification of Computer Applications and Quantitative Methods in Archaeology

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Abstract

Context in archaeology is a theory of inclusion, differing from context in computer science and other fields where context is a theory of exclusion or only part of a whole. Context is multidimensional, each layer of which is embedded and overlapping in multiple scales, constituting the dimensionality of archaeological research. Context as theory defines relevancy and theorizes GIS as a method that organizes this multidimensionality – ontologically based in the site, subsite, feature(s), assemblage(s), artefact(s), and the detail(s) of the artefact – literally, inclusively, everything! GIS layering and sequencing enable modelling and analysis of the multidimensionality of context. Geodatabase hyperlinks and multimedia within a GIS provide synergistic opportunity for alternative curation strategies and (re) connect detached research. A multidimensional, multiscalar perspective of context as theory crosscuts themes and archaeological settings to unify the seemingly fractured character of computer applications and quantitative methods in archaeology.

Keywords: archaeological theory, context, GIS

Introduction

This short essay describes my thinking about context as theory and theories about context over the last ten years. The term context, according to Butzer (1980: 418) and reiterated by Burke (2002: 153), comes from the Latin word *contexere*, meaning "to weave" and is related to *contextus*, which indicates "connection." Context as theory grew out of archaeological boundary-crossing research into the North American and Mesoamerican Protohistoric Period that found me juggling incommensurable paradigms with their extreme and mutually exclusive theories (Bowers 2011; Bowers 2012; Bowers 2014; Pickering 1995: 186-192) and a recognition of the converging need to theorize complex projects involving multiple scales and methodologies in archaeology (Renfrew 1990: 663; Renfrew 1993: 5, 8, 14; Renfrew 1994: 3, 5, 9-11)and the use of geographic information systems (GIS) in archaeology (Lock 2001; Lock 2003; Wheatley 1993; Wheatley 2000). This may stem from inaccurate understandings that conflate qualified and unqualified context, which are discussed here. Also, periodic synthesis of conflictive and confusing theory as well as reconciliation of ideographic and nomothetic research, it should be noted, are part of the science process (Huxley 2010 [1942]; James 2010a; Mayr 1982; Peebles 1993).

The application of context as theory to research detachment was inspired by my research of the Garoga Site in Central New York State, which was discovered in the nineteenth century and has been periodically researched across the entire span of archaeology as a profession, and the session abstract of Pouncett, Reilly & Stead (2016), titled "Digital Archaeology - Where are we and how do we fit in?" that expressed concern about the "fractures and silos" of "computing and digital technologies" in archaeology. The perceived silo effect and fractured nature of computer applications and quantitative methods in archaeology is a feature of all archaeological research, indeed of all science (Pickering 1995: 2-3). Research detachment is a product of the research context that (hyper)linked GIS-based archaeological geodatabases can (re)connect, maintaining the metadata necessary for scientifically useful curation. This essay introduces innovative concepts, such as tense theoretical continuums and the dispersion effect, from my thinking about context as archaeological theory to archaeologically theorize computer applications and quantitative methods for archaeology and argue that a GIS-based solution can resolve or at least improve the problems of research detachment (geographically, linguistically, and physically) and enable alternative curation strategies.

Research Detachment

Geographical Research Detachment

Research detachment is a barrier to knowledge creation, which affects and is affected by the research context. Three of the ways that research becomes detached are: geographically, linguistically, and physically. Archaeology is a global endeavour, so requires access to materials and knowledge that may be geographically located anywhere in the world. The archaeological site, the artefacts, the documentation, and the data from that site as well as the researcher or researchers are likely to be in three or more different geographic locations, which may be relatively local or dispersed across the globe. This situation can be referred to as the *dispersion effect* of archaeological research and it is the primary cause and condition of geographic detachment.

The dispersion effect is greater for important and large sites with multiple funding sources that have involved many researchers from around the world, such as Çatalhöyük (Hodder 2008). New York, on the other hand, which does not have any archaeological world heritage sites (only the Historic Period Statue of Liberty), is impacted by geographical dispersion to a far lesser degree. Snow (1995: xi, 1-4) undertook an effort in 1984 to locate artefacts and documentation from Mohawk Valley sites, including Garoga, and found that the majority were located in New York, but spread amongst more than a hundred collections, most of them private. Collections from Mohawk Valley sites outside of New York are still located within the United States, at the Peabody Museum of Harvard in Massachusetts and the collections from the National Museum of the American Indian in New York City that were relocated to establish the Smithsonian National Museum of the American Indian (NMAI) in Washington, D.C. (Snow 1995: 3-4, 113-117, 156-157). It requires the time and funding for travel to overcome the dispersion effect and when this involves crossing international boundaries, is impacted by the current political context.

Another issue due to geographical detachment is that researchers working on the same site or the same idea from different parts of the world may be unaware of one another. This can lead to unnecessary duplication of effort instead of a collaborative effort toward knowledge production. This effect is further compounded when researchers approach the same site or idea from different academic disciplines or archaeological specializations, an effect that Marcus (1983: 454, 456-457, 480-481) noted more than thirty years ago in Mesoamerican archaeology. We form associations, such as Computer Applications and Quantitative Methods in Archaeology (CAA), to reduce unnecessary duplication of effort through networking and interface (Goodrum 2009). This strategy is often successful but is impacted by linguistic detachment.

Linguistic Research Detachment

English is the *lingua franca* of science and therefore, of archaeology. Huang and Chang (2008: 1824-1825, 1827) demonstrated that there is an indexing bias against scientists who publish in a language other than English. And two more recent studies done by the University of Wolverhampton in England demonstrated that science researchers who use Mendeley citation software tend to read English language literature published in their own country rather than publications from other countries, even when English is not an official language of their country (Fairclough and Thelwall 2015; Thelwall and Maflahi 2015). The historical solution to language differences in archaeology is translation. The lake(shore) dwellings of Switzerland, known since 1472, were systematically excavated by Ferdinand Keller in 1853 and his first report published in the proceedings of the Antiquarian Society of Zürich the following year (Keller 1854; Menotti 2001: 319-320). The sixth report was published in 1866, the same year that Lee compiled, edited, and translated Keller's reports from the original German to English (Keller 1866; Lee 1866). Keller's published site reports have never been translated into English. This can lead to a situation where the primary literature is not cited in English-speaking locations. Rather, Lee's (1866) edited translation is cited or worse, secondary sources such as Menotti (2001) on Keller are cited. Additionally, only works considered important are translated and there may be works that, while perhaps less important at the time of their writing, are now important because of recent scholarship and are completely detached because their existence is unknown or unreadable by the current researcher(s) because of the language barrier.

Temporal Research Detachment

Thus, the research context is impaired by linguistic detachment and is also affected by the practice of citing only the most current literature because archaeological careers are tied to citations, an example of temporal research detachment (Smith et al. 2015). Temporal research detachment can be thought of as the taphonomy of archaeology. Older archaeological research either decays through disuse and detachment or becomes fossilized through the secondary literature. According to Marcus (1983: 480), Maya archaeologists "lack awareness...[of] the older stages in the history of their own subdiscipline," contributing to a stagnant, circular research pattern in Mesoamerican archaeology. The traditional solutions to the problem of temporal research detachment are indices, bibliographies, citation, and more recently, searchable databases, which require entry accuracy or the search algorithm will be unable to retrieve the document, so that it becomes functionally detached. Providing hyperlinks to every document, publication, and other forms of media related to a site in a globally linked geodatabase along with the ability to translate those media into any language at the click of a button, however imperfect the translation might be, will help to prevent older research from becoming detached. Additionally, it will save future researchers time and money searching for documents that may be held in repositories anywhere in the world.

Physical Research Detachment

More serious than the temporal detachment of published literature is the physical detachment of data loss, which is sometimes related to time and taphonomy. Archaeological data is lost at an alarming rate through warfare, deculturizing and demoralizing the enemy by intentional heritage destruction (Bokova 2015; Gerstenblith 2016). Data can become physically detached due to natural processes or a combination of natural and anthropogenic processes, such as the erosion of coastal and maritime archaeological sites (Erlandson 2012). Data can be physically detached through theft or looting by groups and individuals, including archaeologists, for personal gain or economic subsistence (Proulx 2013; Saad El-Gendi 2012; Schier 2011). Archaeological data detached through looting and theft is sometimes reattached when that data is returned such as the Fremont clay figurine returned to the Utah State University-Eastern Prehistoric Museum after being detached for almost forty years (Lobell 2012). Finally, archaeology is a destructive science that can result in detached data through poor excavation techniques and inaccurate or incomplete documentation. Digitization and digital redundancy, linked through a GIS geodatabase will help reduce risk and protect at least some types of archaeological data from complete loss by physical detachment.

Curation Context in Crisis

The curation context adds another dimension to archaeology. Curation includes everything archaeologists do with their data after excavation other than analyse it (e.g., cataloguing, disseminating, displaying, educating, and otherwise engaging stakeholders). The curation context is an intersection point of archaeology with everything and everyone else and facilitates both storage and access to archaeological data. The curation context is in crisis. There is insufficient space to store the millions of archaeological artefacts excavated over the last couple of hundred years, let alone those being excavated today and those that will be excavated in the future.

Members of the New York Archaeological Council are working on guidelines for culling artefacts in the field and laboratory, primarily from historic sites, where at least the decision is being made by archaeologists and not museum staff that may not be trained to recognize the scientific value of archaeological artefacts. The current thinking is to cull large quantities of redundant materials, such as nails, bricks, and industrial slag in the field after counting, weighing, sampling, photographing or filming, and documenting. The visual documentation could be used in educational and heritage recreation projects, including virtual and interactive exhibits. The concept relies on that information to be available to archaeologists in the future, but there is no plan yet for how that will happen. Digital connection through a globally linked geodatabase would ensure that future archaeologists anywhere in the world would have access to the related documentation and could even (re)excavate the original materials if they were needed because documentation would be available to locate the culled material on a map.

We cannot know now what may be important in the future. New York archaeologists that excavated in the mid-twentieth century without stratigraphic control considered all unworked bone to be "refuse" and there was little more they could do with it beyond identification and calculating species frequency. More sophisticated methodologies of extracting information from bones have been developed since then, but it is rare for researchers to weave legacy collections into more recent research projects. Legacy collections in museums and repositories around the world become detached from later research, forgotten in the handwritten catalogues and indices of the past. Hyperlinked archives, museum catalogues, publication databases and the multimedia capability of GIS provide synergistic opportunity for alternative curation, such as virtual exhibits and digital curation, facilitating research and (re)connecting legacy collections.

Context as Theory

The essay up to this point has detailed the problem of research detachment. Additionally, some suggestions as to how GIS can improve the situation have been offered. There are no doubt other ways of protecting archaeological data and reconnecting detached research, which will come to light through continuing work with GIS by archaeologists. The essay will now turn to archaeologically theorizing GIS. The lack of a defined theoretical connection between GIS and archaeology has resulted in a silo effect where archaeologists working with GIS are disconnected from the rest of archaeology. This section attempts to explain the difference of context as theory and theory about the dimensions of context that may theoretically empower archaeologists to move forward with projects that will increase the capacity and capability of GIS to restore and maintain context for archaeologists in the future.

Context as theory defines relevance. While a researcher can define the parameters of the research project, the context exists, having been created through all of the previous research about the theories, methodologies, topic(s), material(s), and site(s) that are being examined in the current research project. For example, there are more than fifty publications about Garoga as well as unpublished documents (e.g., field notes, maps, manuscripts, drawings) held in multiple repositories. All have some relevance to future research about Garoga, though the intensity of that relevance varies by project. All must be included as context for the current project because new research must explain how it complements, supports, or refutes previous research. Every project, each bit of knowledge created, becomes a part of the context for future research. Besides the relevance of previous research about a specific archaeological site, there is also the relevance of previous research about materials (e.g., bone, stone, ceramics), topics (e.g., diet, settlement, demography), methodologies, and theories, though the system of citation allows the exclusion of all but the most recent research because it is assumed that earlier work is already incorporated into the conclusions. The relevance of these is defined by the dimensions of context, which are project-driven and optional, and explains why context appears polysemic in archaeology.

Dimensionality of Context

The term "context" is seemingly polysemous in archaeology but is not at risk of "*hypertrophie*" because it is unqualified when referring to context as theory

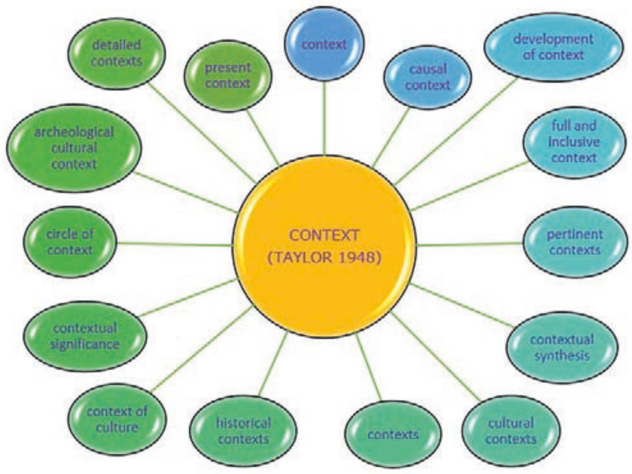

Figure 1. Polysemic constellation of context (after Taylor 1948).

and qualified when referring to the dimensions of context (Chouquer 2013). Taylor (1948: 111) wrote about the "circle of context" as well as using context in more than a dozen other ways, with context in the singular generally denoting an overarching concept related to the reconstruction of past culture and context in the plural to describe the dimensions, here modelled as a constellation in Figure 1. Context related to function was discussed by Phillips and Willey (1953: 616) and Binford (1962) coined "functional context" for his theory of tool use. Schiffer (1972) discussed "archaeological context," "systemic context," and "secondary context." Beginning in 1978, Butzer (1978; Butzer 1980; Butzer 1982) was writing about an ecological "contextual approach." Hodder (1992) wrote about "contexts of rapid site destruction," a social and symbolic "cultural context," "contextualization," and a "contextual archaeology" Ingold (1993) introduced "taskscape," a task-oriented context, into archaeology. Archaeological stratigraphy was the focus of Harris and associates' (Harris 1979; Harris 1989; Harris et al. 1993) writings about context and stratigraphy, followed by the "structured deposition" of Richards and Thomas (1984) and stratigraphic context in relation to pedasols discussed by Cremeens and Hart (1995). Stratigraphic context was returned to by Stein (2000; Stein 2008: 113-115), which Lyman (2012: 211-212) responded to by defining archaeological context as provenience plus association. The stratigraphy references listed here are theory-based methodologies based on much older theoretical works by Stenonis (1699) and Worsaae (1843), mentioned here to avoid conceptual detachment, which occurs when only the most recent sources are cited for an idea without an attribution to the originator. Most of these theories are solidly based in archaeological practice and can be considered as much data-driven as philosophical because they resulted from the authors' many years of experience in archaeology.

It was my attempt to understand how these various meanings – these dimensions of context – could exist at the same time in archaeology and all be correct (despite sometimes conflicting with one another, they are all accurate and logically consistent within themselves) that led me to recognize that the only way this could be possible is if context was theory (Parsons 1979-1980; Sutton and Staw 1995). Specifically, that context as theory defines relevance throughout the research process and all these theories about context define various aspects or dimensions of what may be relevant (i.e., defining the relevance for topics and materials) to a research project. Where Ritchie and Funk (1973: 1-2) and Taylor (1948) did not recognize that context is something that emerges from the work of many archaeologists through time (Taylor 1948:79-82, 94), Hodder (1986) and Lock (2003) did not distinguish between theoretical context that *must* be included and the *optional* inclusion of any or all of the dimensions of context, though Lock has envisioned how GIS maintains context and enables the exploration of context at multiple scales (James 2016; Lock 2003: 12). Context explains what archaeologists do and why we do it, connecting epistemology with praxis (Hodder 1992: 4; James 2016). Context is able to do this because it is polysemic, it is "good to think" with (Lévi-Strauss 1964: 89) providing "enlightenment" (DiMaggio 1995: 391). These examples demonstrate that in praxis, archaeologists have tested their hypotheses and ideas about context in every project and created middle-range theories to access particular aspects of context (Binford 1981). Both theory and methodology as well as context as theory and the dimensions of context are necessary if archaeology is to create accurate knowledge.

Archaeology – at least in praxis – has been increasing the dimensionality of context. Initially two dimensional to the culture historians in the mid-twentieth century – an object in space and time – context was relatively easy to represent with two

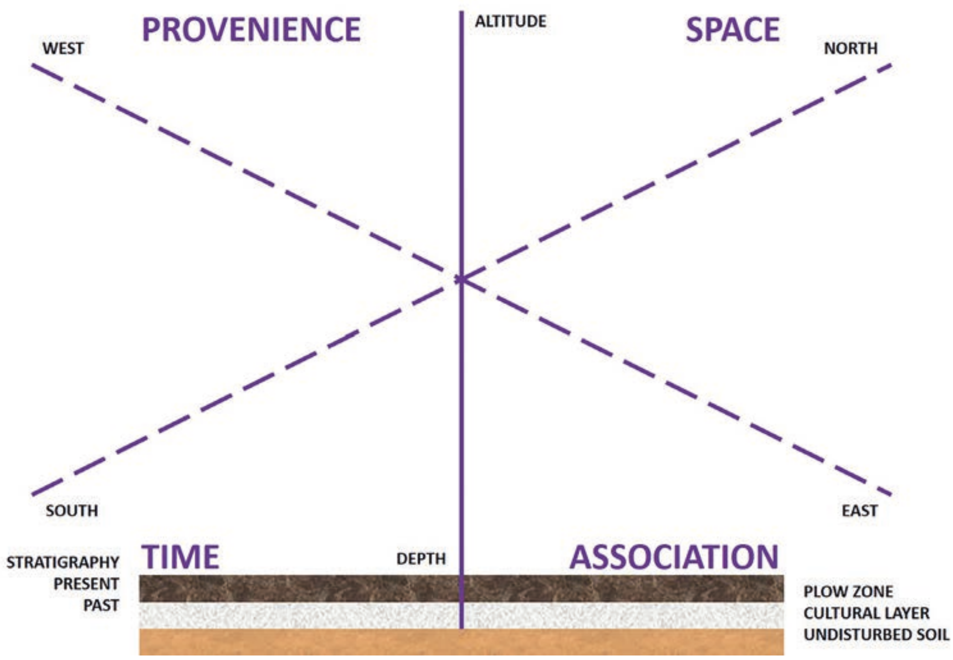

Figure 2. The seven dimensions of archaeological description.

dimensional models such as diagrams and maps. The end of the twentieth century was marked by models of the three dimensions of human visual perception – verticality, horizontality, and depth – often for public display. The twenty-first century brought innovative models, such as the space-time cube extension, which is a three-dimensional structure that may have analytical potential (Huisman et al. 2009; Kveladze, Kraak & Van Elzakker 2015). Lyman's (2012) definition of archaeological context as the three dimensions of provenience – longitude, latitude and depth (as a proxy for time) – plus association includes four dimensions of context. Butzer's (1978; 1980; 1982) "refined contextual paradigm" maps onto a four-dimensional tesseract and De Roo and associates (De Roo et al. 2013; De Roo et al. 2014; De Roo 2016) have been developing a methodology for a four-dimensional GIS that displays three dimensions of space plus time. Green (2011: 69) discussed thinking of fuzziness as a fifth dimension of a temporal GIS or tGIS. Considered together, these theories demonstrate that there are more than five dimensions in archaeology; thus, context is multidimensional.

The foundational epistemological stance of archaeology is that something can be known through studying the material traces of the past. This does *not* say that something can be known *about* the past through archaeological research. While it is true that archaeology produces knowledge about the past, it also produces knowledge of the present and sometimes of the potential future, which all impact interpretation. Time, alone then, is three dimensional in archaeology. Thus, time and the four dimensions of archaeological context (depth being factually independent of time due to taphonomy) account for seven dimensions of context, which are illustrated in Figure 2, before moving beyond the merely descriptive. The temporal dimensions of past and present overlap the archaeological context at depth, stratigraphy, and association. Context as archaeological theory organizes this multidimensionality and is ontologically based in the site, subsite, feature(s), assemblage(s), artefact(s), and the detail(s) of the artefact – literally, "context is everything in archaeology" (Conard et al. 2008: 236).

Context in archaeology differs from other fields that view context as being the surroundings of an object that are examined to understand the object, the *exclusive* perspective. Archaeology takes the *inclusive* perspective that there is a bidirectional, interactive relationship between objects and their surroundings (i.e., both are relevant), and it is as necessary to examine the object to understand the surroundings as it is to examine the surroundings to understand the object (Hodder 2012). Archaeology takes into consideration multiple dimensions of context, including: the research context (the conditions under which research is conducted), the archaeological context, the geographical context (past or present political designations), the ecological or environmental context, the social context, the taphonomic context, the curation context, the hermeneutical or interpretive context, and the "institutional context" defined as: "the provenienced archaeological site or subsite where a specific type of operation occurred in the past that is identified by associated features and artefact assemblages" (James 2015; James 2016). These are the spaces and places that for all of their variability in appearance from site to site, are archaeologically recognizable as institutions and are often denoted in the literature as "ritual contexts," "domestic contexts," "production contexts," and so on. And as Turner (1997) informed us, *Homo sapiens* have a long history of creating institutions. Each layer of these contexts is embedded and overlapping in multiple scales, constituting the dimensionality of archaeological research. The dimensionality of context forms the interwoven texture of the tapestry we call the archaeological record, which is written through the contributions of every archaeologist working ideographically and nomothetically on their particular thread over the last hundred or so years under a variety of theories and methodologies, providing the complementary and contrasting colours, thin and thick descriptions, and overlapping conceptions of what it has been, is, and could be to be human (James 2010b; Ponterotto 2006).

Tense Theoretical Continuums

Both processual and postprocessual archaeology are valid epistemologies and there is nothing in either that precludes the use of the other and using both may be more productive than either alone. The same can be said of modern versus postmodern, objective versus subjective, anthropology versus history and all other debates that compare the two endpoints of a theoretical continuum. Additional tension is exerted on theoretical continuums by scale (e.g., artefact, assemblage, site), and the general versus the particular (Hodder 1992: 4). Tense theoretical continuums create boundaries that empower knowledge creation and knowledge emerges from the tension. The many theories that exist between the tense endpoints are modulated, are pushed and pulled, by tensity shifts between the extremities. The theoretical structure, the frame, is strengthened through the research process and the tapestry of knowledge emerges, is created, and incorporated into what it is to be human. Context is that theoretical structure, and it explains why context is everything in archaeology. Just as a tapestry requires the warp threads to remain tied tautly to the frame during the weaving so the emerging representation is not distorted, the threads of every archaeological research project are kept taut by the frame of context so that our representation of what has been in the past, is now, and perhaps will be in the future to be human remains clear.

Theorizing Geographic Information Systems for Archaeology

It is generally believed that archaeology does not write theory, but only transforms theory imported from other fields (Lyman 2007). Most archaeologists have focused on middle range theory or the development of methodology (e.g., Binford 1977: 1-10; Merton 1949: 39-53). It is no surprise then that Wheatley (1993; Wheatley 2000) and Lock (2003: 1-12), looking to archaeologically theorize geographic information systems (GIS), found little archaeological theory and lots of functional methodologies (Lock 2001). One reason is that many methodologies can operationalize a single theory. Another factor is the call from big data science for data-driven in opposition to theory-driven research, though this is a tense theoretical continuum, paralleling Wheatley's finding that GIS is often thought to be a theory-neutral methodology, though there is no such thing (Kitchin 2014; Wheatley 1993: 133-135). Generally speaking, GIS is theorized by an array of cartographic and design theories as well as theories from mathematics and computer science. and it is hoped that the previous discussion about context will theoretically connect archaeologists creating and/or using GIS in their research to other archaeologists because all of archaeology is connected through context and the many dimensions of context.

GIS is particularly well-suited to restore and maintain context. GIS layering and sequencing as well as recent advances in three-dimensional voxel mapping enable modelling and analysis of the multidimensionality of context (Noon 2012). As scientists, we want things to be perfectly functional and there are various individuals and groups working towards a true temporal GIS. But as archaeologists, we are used to dealing with uncertainty and can make do with what we have available, though a full discussion of this is beyond the scope of this essay. GIS enables multiple layers of data to be visualized separately and together. Layers can be named and features labelled to display the various contexts in different time periods. Artefacts can be displayed within features and features within sites. Hyperlinks can attach documents such as field notes and publications, photographs, videos, drawings, two and three-dimensional reconstructions, vertical perspectives, and other unique archaeological data to a map that is temporally based on the excavation along with a layer or multiple layers that are based on known landscape differences, such as changed waterways and coasts – even when those documents are maintained outside of the geodatabase. By changing scale, we can visualize regional social relationships – the trading, alliances, and antagonisms of human life in the past. These are just a few examples of the possibilities for GIS in archaeology. The ability to connect different types of data, however imperfectly, also applies to detached research. To describe it mathematically:

$$R_d = -C + -c$$

where Rd is research that has become detached, C is unqualified context, and c is qualified context. Restoring and maintaining connection to archaeological data and analyses is vital because it is the context that archaeology relies on to inform future research.

Closing Remarks

A multidimensional perspective of context as theory crosscuts themes and archaeological settings to unify what only appears to be the fractured character of computer applications and quantitative methods in archaeology. The digital preservation of archaeological data, including GIS data, is already moving towards national-level unification, exemplified by the Digital Archaeological Record (tDAR) in the United States and the Archaeology Data Service (ADS) in the United Kingdom. There are still many different tasks to be accomplished to build a globally linked geodatabase, to provide the capabilities to visualize archaeology, and to secure the data while providing appropriate access to archaeologists. The different types of projects that are being done by CAA members are needed if we are to move beyond description into analysis and knowledge creation. Context is the theory that unifies all archaeology – from the excavation to the documentation through visualization and analysis to research dissemination, publication, and public engagement. No one archaeologist can do it all, no one lifetime is sufficient, but through time and continued research, the past, present, and future will be globally accessible. New vistas of research possibilities will open. Every archaeologist contributes to the tapestry, whether with a long or short, thin or thick, flat or braided thread. Every archaeological project brings the weaving into clarity or highlights an area where clarity is needed. It is context that frames the tapestry, holding all of the archaeological threads taut as each generation of archaeologists weaves their data and interpretations into the archaeological record. All archaeological research is connected through time and space by context as theory.

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Publishing an Archeological Excavation Report in a Logicist Workflow

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Abstract

The logicist programme, which was initiated in the 1970s by J.C. Gardin, aims: first, to clarify the reasoning processes in the field of archeology; second, to explore new forms of publication, in order to get over the growing imbalance between the flood of publications and our capacities of assimilation. The logicist programme brings out the cognitive structure of archaeological constructs, which establish a bridge between empirical facts, or descriptive propositions, at one end of the argumentation, and interpretative propositions at the other end. This condensation process opens the way for alternative forms of publication, designed to speed up the assimilation of the chain of inference and the consultation of the database on which it stands. In this paper we propose a new publishing workflow respecting the principles of the logicist programme. We show how texts are encoded using XML markup in accordance to Text Encoding Initiative (TEI) recommendations. We explain how the relations between propositions are marked-up as hypertext references with simple qualification. Next, we describe how to extract the overall organization of the interpretation process from the XML tree as RDF triple by extrapolating from relations' links. We also show how to produce an overview diagram representing the interpretative process.

Keywords: archeological constructs, logicist workflow, XML, TEI, RDF

Introduction

It is now widely recognized that the quantity of pages currently published in our areas of research is such that we are unable to read more than a very small fraction of the literature relevant to our research interests. Instead, we consult some of it, following our own selection strategies. The paradox is that while we are perfectly aware of this phenomenon, we continue to write as if our works were to be read, without any attempt to redraft them for the alternative perspective, that is consultation. Digital publishing as such does not solve the problem; it makes it worse.

The logicist programme, which was initiated in late 1970s by Jean-Claude Gardin (Gardin 1979; Gardin 2003), was developed with a twofold aim: first, to bring out the logico-semantic structure of interpretative constructs in archaeology, in order to clarify the reasoning processes; second, to explore alternative forms of publication in order to overcome the growing imbalance between the flood of publications and our assimilation capacities. The logicist programme brings out the cognitive structure of archaeological constructs, which establish a bridge between empirical facts, or descriptive propositions, at one end of the argumentation, and interpretative propositions at the other end. This condensation process opens the way for alternative forms of publication, designed to speed up the assimilation of the chain of inference and the consultation of the database on which it stands.

The aim of this paper is to bring forward a new publishing workflow based on the principles of the logicist programme. We first show how the texts are

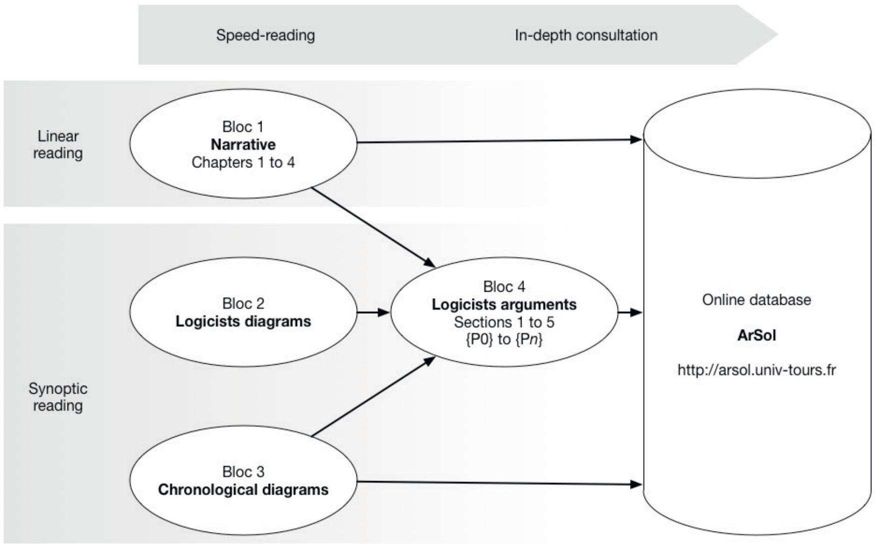

Figure 1. The logicist approach of the publication of the excavation of Rigny.

encoded using XML markup in accordance with (TEI) recommendations, and then how the relations between propositions are expressed as hypertext reference markup with simple qualification. Next, we describe how the overall structure of the interpretative construct, represented by an inference diagram, is extracted from the XML (eXtensible Markup Language) tree as RDF triple by extrapolating from the interrelation links. The digital publication of the archaeological excavation of the settlement and church in Rigny (Indre-et-Loire, France) (Zadora-Rio, Galinié et al. forthcoming) is used as a test-case to show that our workflow can provide different levels of information retrieval, allowing both speed-reading and in-depth consultation.

The Logicist Programme: A Reminder

The logicist programme is a long-term research project launched by Jean-Claude Gardin (Gardin 1979; Gardin 2003). Archaeological constructs are considered in the logicist approach as computational structures made up of two constituents: 1) a data base, i.e. a set of declarative propositions {P*0*} generally relating to empirical facts; 2) an inference tree expressing the steps leading from the initial set of propositions {P*0*} to the conclusions {Pn} through a succession of leaps {P*i*} => {P*j*} from one or several levels of the inference tree to the next. Such a tree can be read in two alternative directions: empirico-inductive, from the database {P0} to the conclusions {P*n*}, or hypothetico-deductive, from the hypotheses {P*n*} to the database {P*0*}. The logicist framework helps to apprehend the overall organization of the interpretation process and to consult readily some of its parts without having to go through lengthy presentations in standard archaeological discourse.

The First Editorial Developments in the Field of the Archeology of Techniques

The first editorial developments emerged in the early 2000s, with the creation of a new collection under the title “Référentiels” by the Éditions de la Maison des sciences de l’Homme in Paris, in partnership with “Épistèmes”, a private firm founded by Philippe Blasco. The first three publications, in the field of the archeology of techniques, were designed as hybrids: a printed book with a CD-ROM containing its cognitive substance (data and inference tree) in a multi-media format based on the logicist framework (Scientific Constructs and Data), designed by Valentine Roux and Philippe Blasco (Roux 2009; Roux and Blasco 2004). The creation in 2007 of an international online journal, The Arkeotek Journal, and the launching of the Arkeotek project in the domain of the archaeology of techniques, under the direction of Valentine Roux, aimed at the developing of “logicist corpuses” made of documents structured in data and interpretation rules (Gardin and Roux 2004; Roux and Aussenac-Gilles 2013).

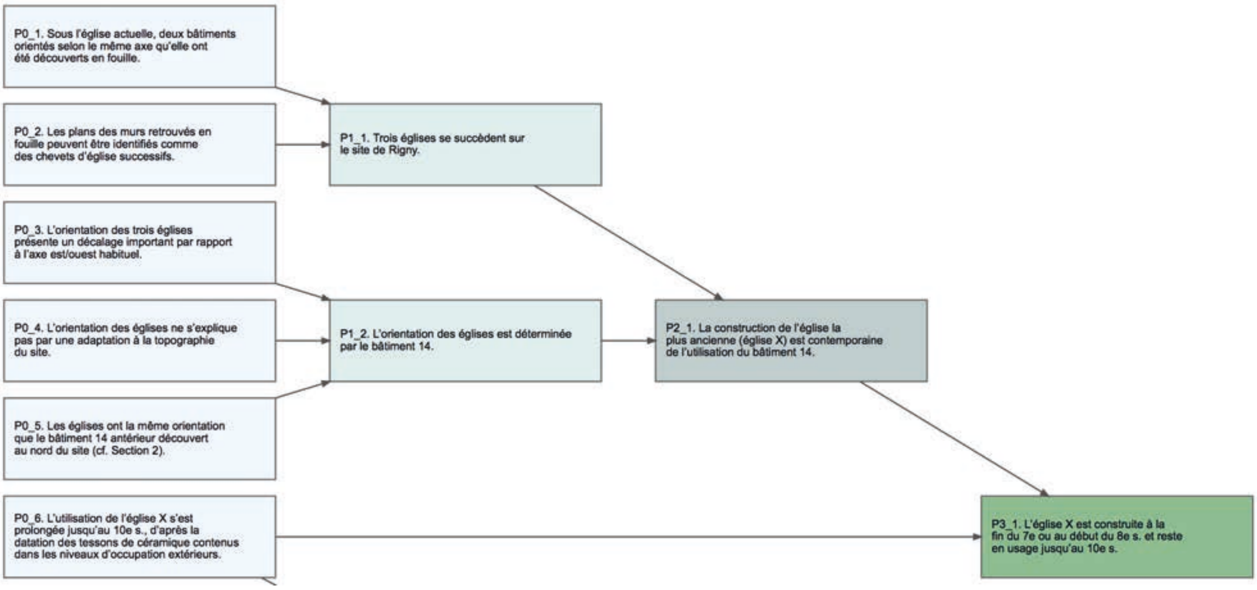

Figure 2. A fragment of a logicist diagram.

Applying the Logicist Framework to the Excavation of the Settlement and Church in Rigny

The results of an archeological excavation are the outcome of a cognitive process which is quite different from that of the archeology of techniques, since neither the selection nor the analytical framework of the corpus can be predetermined. The interpretation of the excavation data primarily consists in identifying the archeological remains ("what is there?") by ascribing to them a date, a function, and a possible morphological reconstruction. The next step consists in reconstructing the sequence of activities and events (including site formation processes) in order to answer to the question: "What happened there?" and to examine its implications in a broader historiographical context. The reading of published excavation reports is especially unrewarding and painstaking because of the lengthy descriptions of the remains, motivated by the irreversible character of excavation activities, and difficult access to the primary documentation. The need to rethink the form of archeological publications emerged in the 1970-1980's, but it is only the development of the Internet which allowed the recent online publications of databases and site records, thus opening new perspectives and possibilities.

The publication of the archaeological excavation of Rigny represents a new experiment in the "Référentiels" collection, not only because it will be the first one dealing with the results of an excavation, but also because it will be the first one to be entirely digital (Zadora-Rio, Galinié et al. forthcoming). The publication is divided into four interconnected sections, each one representing a possible access point to the content (Figure 1). The three sections in the left column ("Block 1" to "Block 3") represent different forms of speed-reading while the fourth one in the middle ("Block 4") contains a comprehensive list of all the statements, from the empirical facts (or initial propositions {P*0*}) to the conclusions (or final propositions {P*n*}).

The "narrative" ("Block 1"), which contains the methodological and historiographical considerations together with a rapid and linear outline of the results, is connected by hypertext links to the "logicists arguments" from {P*0*} to {P*n*} ("Block 4"). It is designed for speed-reading, but it also allows for the assessment of the argumentation and the retrieval of the data on which it is based if the reader chooses to follow the links. The "logicist diagrams" ("Block 2") give an overview of the argumentation presented in the form of an inference tree displayed from left to right. The hierarchical level of the propositions is indicated by the colourmap, the lightest colour being used for the initial set of propositions {P*0*} and the darkest one for the final propositions (or conclusions) {P*n*} (Figure 2). The initial propositions, or {P*0*}, on the left of the screen, list all the data supporting the interpretation. The following steps, from {P*1*} to {P*n*}, do not introduce new data, but repre-

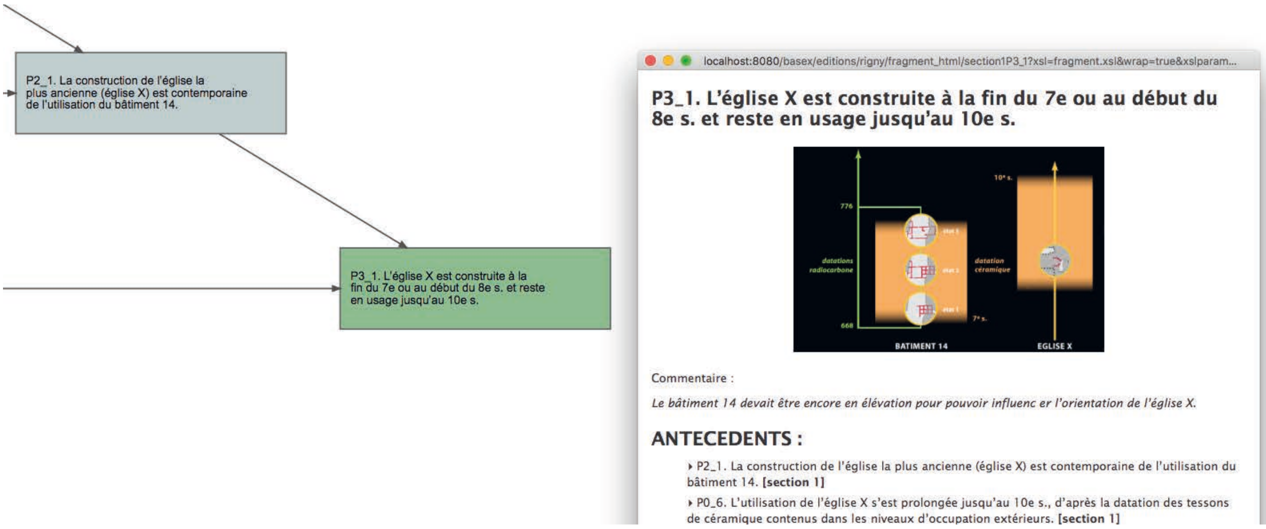

Figure 3. Retrieving the detailed arguments from the logicist diagram.

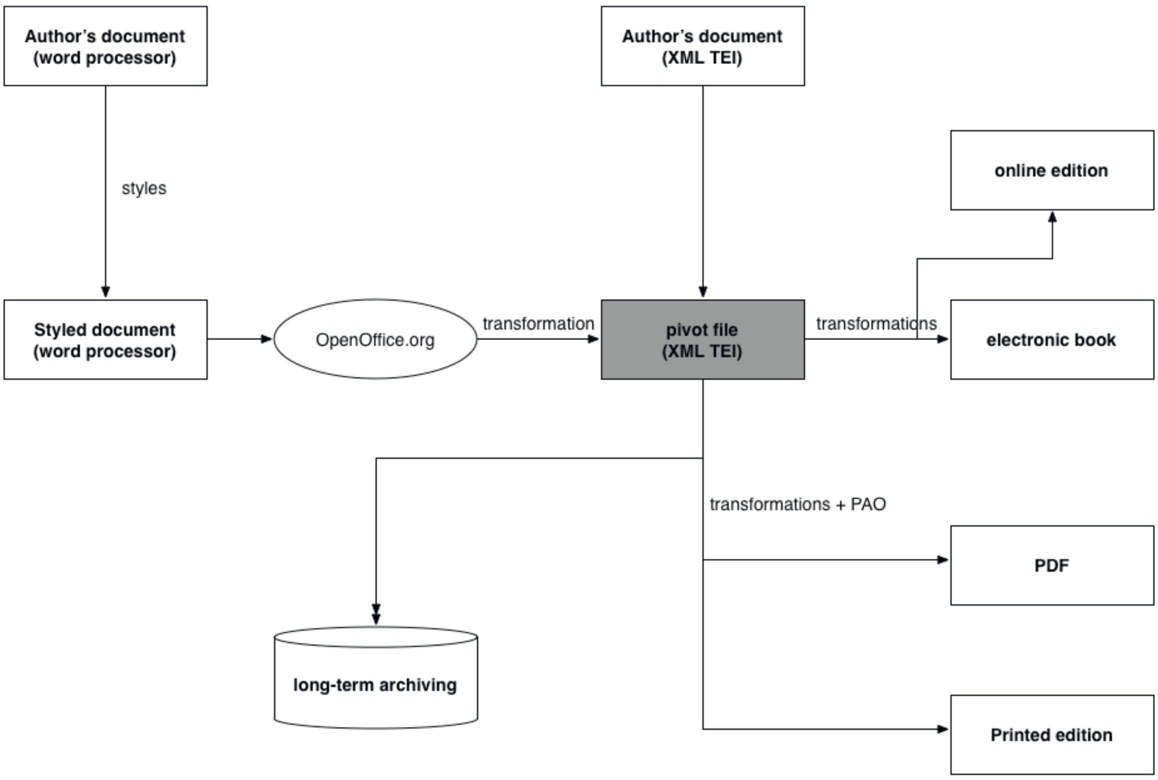

Figure 4. The Single Source Publishing model of the Pôle document numérique and the Caen University Press.

sent inference operations based on the combination of lower level propositions.

Diagrams are interactive: by selecting an intermediate proposition {P*i*} or a final proposition {P*n*}, the lower level propositions on which it is based, are also selected. As shown in Figure 3, a click on one of the boxes of the inference tree enables the access to the detailed argumentation ("Block 4"), which contains the supporting data, and also to the anterior propositions if it is an intermediate proposition {P*i*} or a final proposition {P*n*}. The logicist diagrams thus clarify the reasoning processes, and they also form an access mode especially suitable for consultation.

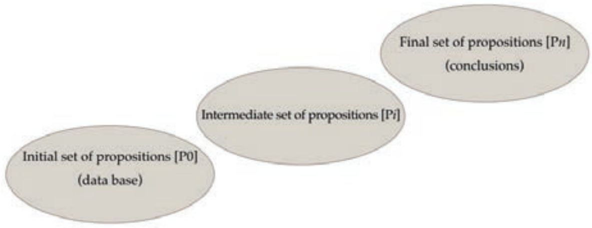

Figure 5. The reasoning process from empirical facts to conclusions.

The Single Source Publishing Model

Publishers have been dealing with multiple media for some years now, which means they need the same text to be readable as a chapter of a printed book, as a webpage, or as a part of an electronic book. In order to produce these multiple versions of a text, publishers are now increasingly inclined to work on a single file that is processed to fit multiple reading media. This method is known as the Single Source Publishing model (SSP) and within this editorial process, from a technical point of view, XML is commonly used to encode the source file.

The *Pôle document numérique* (http://www.unicaen.fr/recherche/mrsh/document_numerique/) and the Caen University Press have built a full SSP workflow based on XML technology, in conformity with the TEI recommendations (http://www.tei-c.org/). Figure 4 gives a general view of the process, leading from the author's file to the multiple reading media.

The framework of the logicist workflow is very close to the SSP model and shares the same work organization (shown in Figure 4). The main difference is that we are dealing with two types of files. The first one is the "narrative", which is, in fact, very close to a classical scientific article. The second one is a set of documents that contains the logicists arguments. These documents contain the statements (or propositions) and the pointers between them. The statements summarize the successive steps leading from one or several levels of the inference process to the next, without any rhetorical apparatus. Pointers between statements provide the links that connect them. The logico-semantic structure of interpretative constructs is thus represented by a sequence of inferences from the initial set of empirical facts, or descriptive propositions {P0}, to the conclusions, or interpretative propositions {Pn} put forward by the author, as shown in Figure 5.

Both the narrative and the logicist arguments are encoded as XML TEI files. While the narrative, which is written in natural language, does not display any special features, the logicist arguments require a specific treatment: whereas the text is encoded in a traditional way, the relations between the statements are encoded as pointers. The section below on "Building the logicist inference tree" gives a detailed presentation of the methods and tools used to develop a user-friendly environment.

For the time being, from a computer science point of view, XML gives the best ratio between expressivity and implementation complexity. It is a format which is extensively used by publishers' in their workflows all around the world. In fact, XML comes with most document types, either natively, or as an imported feature in word processors (.odt, .docx, etc.), on the web (XHTML, HTML5, etc.), in Adobe Indesign, and in epubs. It is a format that has become a real standard when it comes to publishing.

From Texts Flows to Graphs

Whereas XML gives excellent prospects and results in the field of publishing, it lacks expressivity when it comes to building complex relationships and qualifying links between multiple nodes. However, it is possible to express the structure of the argumentation and to prepare the extraction of a network made of all the propositions with the links between them by using some simple XML annotations. Figure 6 gives an XML annotation of a very basic bibliographic reference using the TEI vocabulary. The upper part of the figure displays a bibl element containing three other elements: a *title*, an *author* and a *publisher*. The lower part of the figure gives the strict XML point of view: the "contains" relation is, in fact, the only explicit relation given by the XML tree.

But what we, as humans, really understand about the encoded information within the tree is much more complex. In fact, anyone familiar with XML technology and TEI recommendations understands that we are dealing with a bibliographic reference, the title of which being represented by the text inside the *title* element, the *author* by the text inside the au-

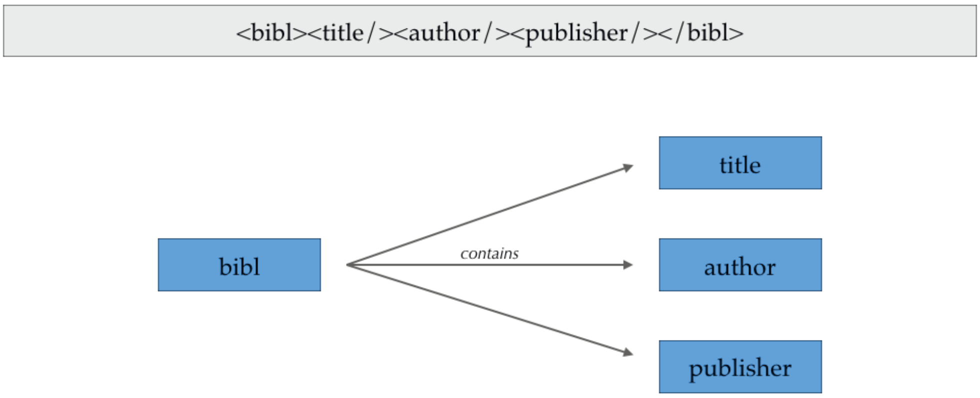

Figure 6. An example of what XML actually says about the data. 6. An example of what XML actually says about the data.

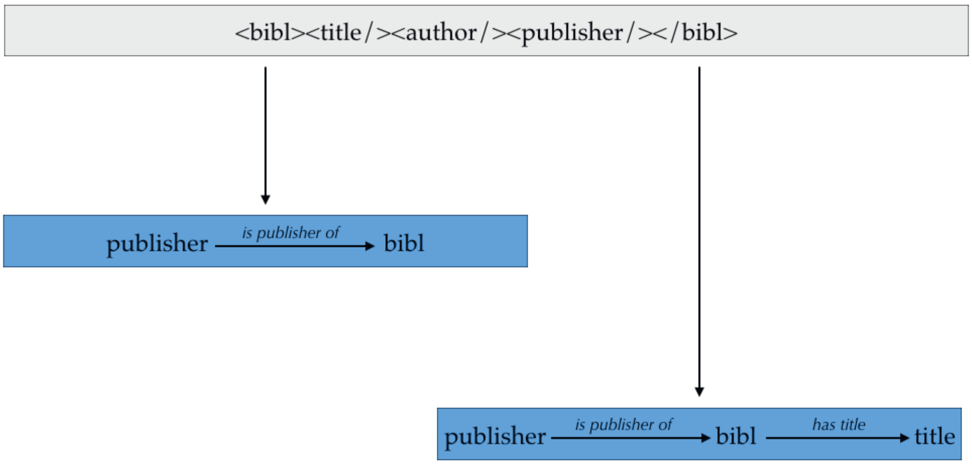

Figure 7. An example of what XML really means about the data.

thor element and the publisher by the text inside the *publisher* element.

Figure 7 shows examples of the interpretation of the XML tree or, in other words, what we, as humans, really understand about the encoded text. The "*contains*" relation between the *bibl* element and the *title* element is actually interpreted as some kind of a "*has title*" oriented relation between the bibliographic reference and the title.

We follow exactly the same pattern to exploit the XML TEI annotations in order to produce the inference tree or interrelationship diagram during the editing process. From a technical point of view, we need to transform the XML tree into an RDF graph to enhance the expressivity of the data set. The interrelationship diagram gives an overview of the interpretative construct, but it also provides an advanced search solution exploiting not only the nodes, or the textual elements, but also the edges, or the relations between textual elements.

Figure 8 provides an overview of the logical process that goes from the XML tree to the RDF graph.

Each proposition is encoded as text division, using the dedicated TEI *div* element with a specific value affected to the *subtype* attribute and a unique identifier, at the file scale, stored in the *xml:id* attribute. Inside this *div* element is another *div* element containing all the links between the current proposition and its antecedents. Each antecedent takes the shape of a pointer element (*ptr*) with a *target* attribute storing the unique identifier of the targeted proposition. The *subtype* attribute is used to store the type of relation we want to draw between the two propositions. In this example the markup builds two relations of the type "is_based_on" between the div identified by "section1P1_1" and the propositions identified by "section1P0_1" and "section1P0_2" which are not visible here, but are stored elsewhere in the XML file.

Using this simple markup for a complete XML tree gives the basis for a full representation of the interpretative construct. The attribute system thus produces some kind of layer, which is added to the XML tree and draws the links between the nodes. In

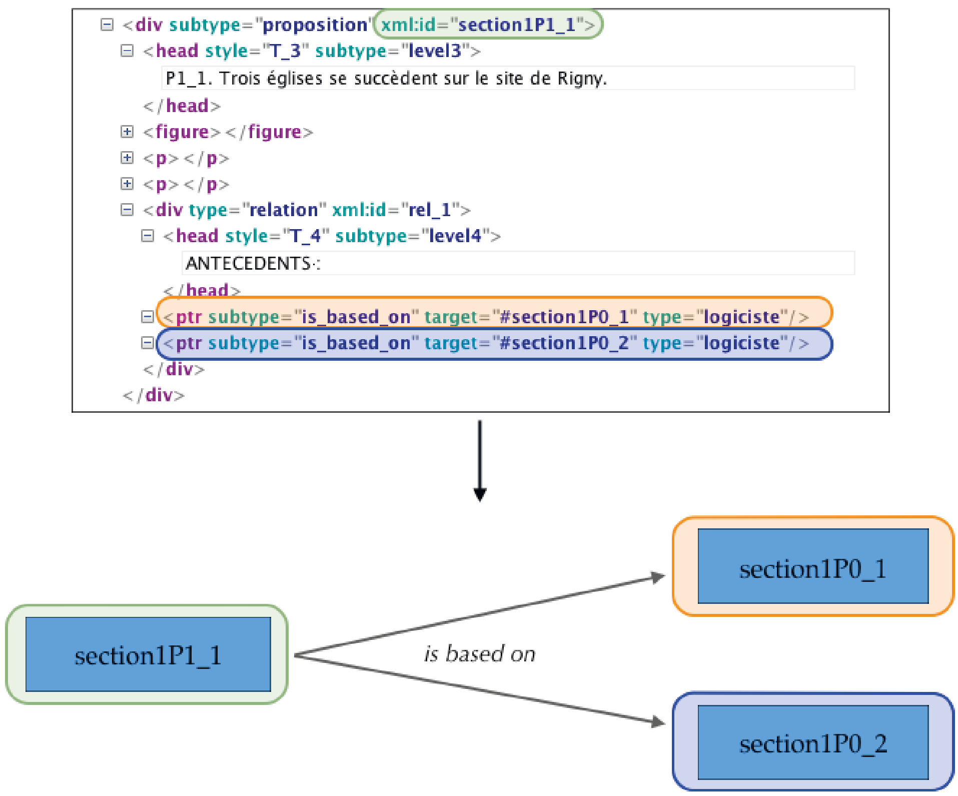

Figure 8. From XML tree to RDF graph.

the following step in the workflow, this network will be parsed to produce the logicist diagram.

Building the Logicist Inference Tree

As we have seen, it is possible to build relations between nodes in an XML tree by using pointers with specific attributes. In order to produce this markup, we developed a dedicated Graphic User Interface (GUI) module for XMLMind XML Editor software (http://www.xmlmind.com/) to allow the archeologist to build the logicist interrelations in a user-friendly environment. This module enables the user to build the relations between the statements belonging to different levels in the inference tree.

The basic pattern of the module is based on the building of a dynamic list of all the propositions that compose the document, sorted by interpretative level. We use the XMLMind XML Editor "commands" system (http://www.xmlmind.com/xmleditor/_distrib/doc/commands/index.html), which is entirely XML, in combination with XSLT (https://www.w3.org/TR/2017/REC-xslt-30-20170608/) (eXtended Stylesheet Language Transformation) and CSS (Cascading Style Sheets) (https://www.w3.org/Style/CSS/) for the text layout. Each node of the XML TEI tree has a form affected by the CSS. Every interpretative proposition, i.e. *div* elements with a *type* attribute associated with each "proposition" and a level with a value superior to 0, is associated with dynamic buttons. To add a relation between an interpretative proposition *A*, which is the subject of the relation, and another one anywhere else in the text, which is the object of the relation, the user has to click on the button associated with proposition *A* to launch the process.

All the steps in this process are parts of a command of the XMLMind XML Editor. The first step is to produce the list of all the propositions by applying a XSLT to the XML document. The XSLT parses the XML document and transforms the propositions into a list that is stored in a flat text file. The second step is to present this list to the user in a dedicated window, so that he can pick the right proposition. XMLMind XML Editor provides a specific *pick* command to do this. When the user chooses the right proposition by clicking on it in the list provided by the *pick window*, a specific XML *pointer* element, ptr with a target attribute, is inserted into the proposition A (See section "From text flows to graphs" above for a complete

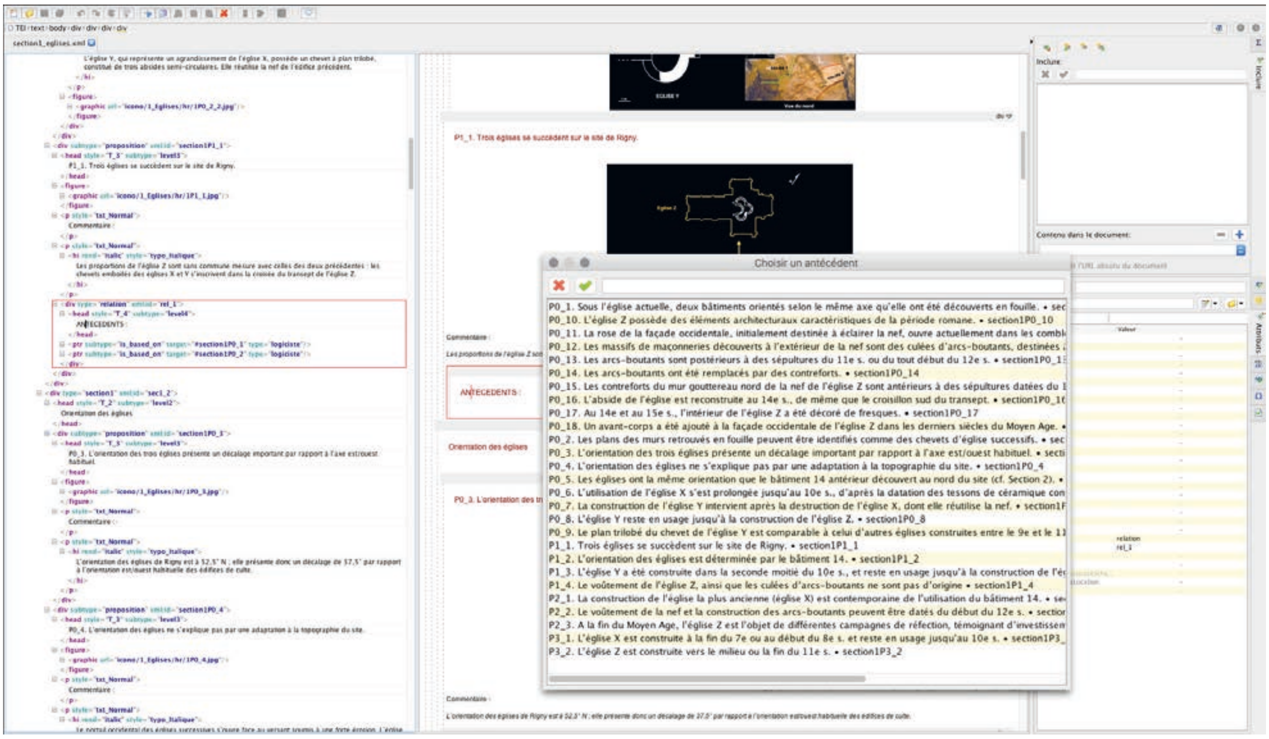

Figure 9. The Graphical User Interface (GUI) for building the relations diagram between propositions.

presentation of the XML markup of the relations between propositions). To add a new relation between proposition *A* and another one, the user only needs to repeat these actions. At the end of the process, the proposition *A* contains its original statement with a group of *ptr* elements pointing to the propositions on which the statement *A* is based upon.

For the time being, the relation qualifications are stored in the *subtype* attribute of *ptr* element and are not dynamics. In the near future we will add a new option to allow the use of custom set of relation types. This collection of pointers does not contain any original text, and must be considered as a new layer of information, which can be used to produce new solutions to retrieve the data and to assess step-by-step the interpretative construct.

In fact, as we will see in the section below, this network of enriched information can be extracted from the XML tree as an RDF graph containing the propositions' titles and the interrelationships between them.

Figure 9 gives an overview of the Graphical User Interface (GUI) developed within XMLmind XML Editor that allows the scholar to build the interrelationship diagram. The *pick window*, with the propositions list, is in the foreground.

From RDF to SVG

In this section we take a close look at all the file formats used in the successive steps of the process ending with the overview of the logicist diagram. At the end of the logicist interrelationship building process, the XML tree is enriched with a collection of pointers leading from interpretative proposition to other propositions, which either belong to the initial set of descriptive statements {P0} or to lower level interpretative propositions {P*n*}. This collection gives us all the necessary information to produce an RDF graph (https://www.w3.org/TR/2014/REC-rdf-schema-20140225/) based on the *subject-predicate-object* expression. Considering the following expression: "the interpretative proposition A is based on propositions B, C and D", where "A" is the *subject*, "is based on" the *predicate* and "B", "C", and "D" the *objects* of the expression, we may thus write it as follows in the RDF/XML syntax:

```
<owl:NamedIndividual rdf:about=”A”>
<rdf:type rdf:resource=”logicisme.xml#Pro-
position”/>
<pddn:Titre>Title of proposition A</
pddn:Titre>
```

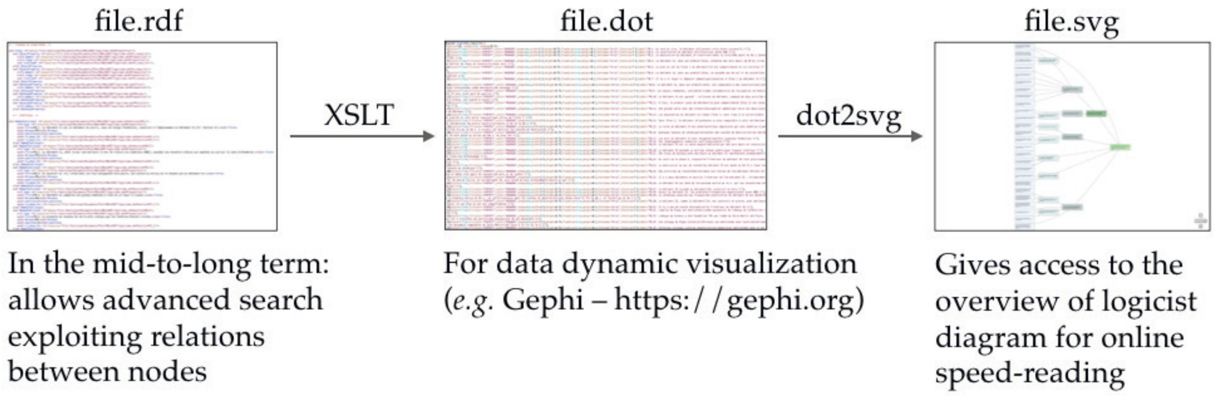

Figure 10. The three file formats used to produce a diagram overview of the interpretative process.

```
<pddn:Niveau>Interpretative level of pro-
position A [superior to 0]</pddn:Niveau>
<pddn:is_based_on rdf:resource="#B"/>
<pddn:is_based_on rdf:resource="#C"/>
<pddn:is_based_on rdf:resource="#D"/>
</owl:NamedIndividual>
```

(The interpretative *level* of the proposition A must be superior to 0, otherwise it would be considered a descriptive proposition).

The RDF file is particularly important in our workflow because it is the basis of our future advanced search engine. RDF adds the possibility of qualifying the relationship between nodes so that it is possible to express constraints on the request. For example, the user can request a specific string in a specific interpretative proposition level with specific relations to other propositions. The RDF is the most expressive file available at our disposal for the time being.

From the RDF file, we then produce a DOT (http://www.graphviz.org/content/dot-language/) file. DOT is a plain text graph format, which is easily written with automatic tools from another file format such as RDF. The main goal of DOT format is to provide a solution to describe graphs with all the necessary information about nodes, edges and specific organization types like ranking for example.

To write the DOT file, we define a set of rules to organize the graph in accordance with both the logicist programme and the specific case of excavation reports. The graph must be read from left to right, starting with the *descriptive propositions* {P*0*} on the left side, and including a new column of propositions for each additional interpretative level from {P*1*} to {P*n*}. This rule set is encoded in a XSLT file that is applied to the RDF/XML file, and the DOT file is the result of the transformation. DOT files can be parsed to draw graphs by using various programs to produce fixed images like DOT, NEATO (command line) (For a complete list, see: http://www.graphviz.org/Documentation.php) or Gephi (Bastian, Heymann & Jacomy 2009) (https://gephi.org/), which give an interactive visualization interface. With Gephi, users can explore and manipulate their data as a network in a fully dynamic environment. The last step of the process is the production of a diagram overview, using Scalable Vector Graphics (SVG) to display it on the publication website. A basic call of the *dot* command produces a well-formed SVG file, ready to be used online. Whereas all the files produced during the process have to be stored, because each one of them provides specific benefits, we need only to write a simple *bash* script to be able to go from the original XML TEI to the SVG with a single command. The final user will of course only have to click on a button in the GUI to invoke this *bash* command and launch the process. Figure 10 gives a short presentation of the three file formats (.rdf, .dot, and .svg) outlining their respective benefits. The RDF file is at the top of our workflow as it contains all the data, the nodes, and explicit relations between the nodes. It is the file that will allow, in the mid-to-long term, the building of an advanced search engine dealing with all the reasoning process and enabling users to formulate complex queries on data sets. The DOT file, which is a descriptive file containing all the necessary information to draw graphs, allows the use of dynamic visualization dedicated softwares like Gephi. With this tool, users may build specific views to explore their data sets. In our workflow, the SVG file is the final shape given to the reasoning process. It is the file which is integrated to the website to give access to the overview of the logicist diagram for online speed-reading.

Conclusion

In this paper we have introduced a new solution inspired by J.C. Gardin's logicist programme, to build, manage, retrieve and assess interpretative constructs. The resulting network of relationships between propositions allows the automatic production of graphical overviews integrated in publication websites in order to provide speed-reading solutions while also allowing for in-depth consultation of basic data and the interpretation process.

We have first implemented this method for the publication of the excavation of the settlement and church in Rigny, and we are currently adapting the rule set to the field of archeology of techniques to meet the requirements of *The Arkeotek Journal*, (http://www.thearkeotekjournal.org/) directed by Valentine Roux, with excellent results. We have developed a complete reusable workflow with a dedicated GUI within the XML editor to add relations between propositions. We are currently adding a dynamic access to the relationship diagram directly within the XML editor, so that the author will be able to access a graphical overview of his inference tree while he is actually building it.

Future work will focus on the integration of the CRMinf (http://new.cidoc-crm.org/crminf/home-4/) module for inference annotation in RDF files. The main goal is to build corpuses of interpretative rules with a shared international standard to describe the relationships between propositions. We also plan to explore the benefits of an internal annotation of propositions, regarding both the concepts and their interrelations, by using the Glozz platform (Widlöcher and Mathet 2012, http://www.glozz.org/) in order to build an advanced search engine.

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Designing and Using Game Environments as Historical Learning Contexts

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Abstract

The virtual presentation of landscapes in games, thanks to the exponential increase of representational power of digital technologies, has been progressively challenging the capacity of gaming audiences to distinguish virtual environments from real-world referents. This spectacular growth, however, has not been mirrored by a comparable progress in the simulation of the natural and social processes from real environments. Although highly realistic, game landscapes in most commercial titles still remain as inert theatrical scenery, devoid of any capacity to reflect the effects of human life agency and the inextricable nature of social and natural processes. In this paper, I present a historical game prototype, developed with the intention of representing the inherent complexity of historical landscapes. The game simulates everyday life in Anglo-Saxon Britain and has been iteratively produced in cycles of development and play-testing sessions with the participation of archaeologists, historians, and educators.

Keywords: games design, game-based learning, serious games, digital history

Introduction

Playing with the past in video games is primarily an engagement with ideas of space. As Aarseth (1997) and Jenkins (2004) eloquently argued, video games central motif is spatial representation, a preoccupation that overshadows the medium concerns on concepts of time, actions, or events. This strong bias sets the medium apart from other means of historical representation, with which games are often compared and judged upon. In video games, the meanings of the past are translated into navigable landscapes, not only to be watched or imagined, but also to be traversed by the player's embodiment in the game world. This ergodic spatial structuring of historical contexts, however, cannot be fully appreciated without the implementation of systems designed to make players 'inhabit' the game.

This paper explores the design of historical game landscapes drawing from the experimental development of a historical game prototype designed to be used as an educational resource in primary school classrooms. In the first section of this paper, Lefebvre's (1991) theory of the social production of space and Tim Ingold's (2000) 'dwelling perspective' on the perception of the landscape are reviewed as main referents for the development of an experimental game prototype. Next, the design process of the game is described according to its most important decision points: historical approach, historical focus, theoretical models/data, and pedagogical orientation. Finally, some initial results and insights from the testing process of the game in a primary school classroom are presented and discussed.

The Production of Game Space

A close look into the history of video games reveals how the medium has evolved, led predominantly by an increasing sophistication in spatial representation. For Wolf (2001), this evolution can be seen as a progressive series of innovations that parallel the development of space in cinema. From the crude computing experiment that first allowed a bunch of pixels to be controlled in a two-dimensional screen, games have move rapidly to the rendering of highly realistic environments constructed with a painstaking level of detail. Realism quickly became one of the major selling points for new games introduced into the market, pushing the computing industry to continually increase its capacity to process and render graphic detail.

Looking at this path in spatial representation, it is easy to become seduced by the beauty and perceptual richness of these virtual environments and to identify complete representational mimesis as the ultimate goal of the medium. Furthermore, as the visual gap between virtual environments and the real world narrows, the natural expectation that follows is the extension of realism to the interactive affordances of the medium. Virtual landscapes not only have to look real but are expected to immerse users in the perfect concretisation of the 'Holodeck', the fictional entertainment system from the StarTrek spaceship, borrowed by Janet Murray (1998) to imagine the future of narrative in computer generated worlds. Although appealing, the problem with this way of conceptualising digital technologies–in particular, video games–has been noted by several authors, leading to long-standing debates about the appropriateness of the metaphor of immersion and the emphasis on narrative as the defining property of the medium. Ultimately, the relationship between the player and the game world is mediated by play, a characteristic that "makes [games spaces] allegorical: they are figurative comments on the ultimate impossibility of representing real space" (Aarseth 2007: 169).

Indeed, the conceptualisation of game spaces is far more complex than what the literal translation from real into virtual space affords to explain. To achieve a better comprehension of how players perceive, navigate, and make sense of historically reconstructed game worlds, more sophisticated theories of game-space need to be revised. Henri Lefebvre's (1991) theory of space offers a good point of departure in this undertaking. For Lefebvre, space is a social product, a dimension that does not exist "in itself" as a separate objective reality. Space is never finished or 'complete'; rather, it is constantly being constructed and reconstructed from the social interactions and everyday practices of people living in it.

To gain a better understanding of how this process works Lefebvre proposed a dialectical model composed of three parts. First, the spatial practice, referring to the perceived experience of living in an urban reality, where networks of communication allow people to move between the places where they perform their daily practices and routines. Second, representations of space incorporates the ways in which space is conceptually conceived by the multiple disciplines that converge in the effort of building descriptions, definitions, and theories about it. Third, representational space refers to the ways in which space is lived, configuring a layer of symbolic associations that overlays the physical space.

The importance and relevance of Lefebvre's spatial theory have been recognised by several scholars but in general terms lacks an adequate level of consistency (Fraser 2011; Crawford 2015). Flynn (1991), for example, makes a first attempt to map the dimensions of space proposed by Lefebvre into game worlds, but his analysis remains at a preliminary stage. Aarseth (2007) also acknowledges the relevance of Lefebvre's theory for the conceptualisation of game spaces, but, recognising the difficulty of strictly mapping Lefebvre's triad into game spaces, does not move this analysis any further. Nitsche (2008) quotes Lefebvre as a reference in the construction of his own model of game space but notes the greater influence of his own experience and conceptions in its development.

In spite of this apparent lack of a serious academic effort in applying Lefebvre's theory to game space, I regard this line of analysis of chief importance to make sense of game spaces in general and to translate historical meanings into ideas of space. First, Lefebvre's ideas provide an analytical frame to look into the spatial practice of players, registered in their movements as they traverse and interact with the game world. Second, Lefebvre's dialectical model provides a conceptual lens to understand game environments as ideological constructions; in the same way that architects and urban planners build representations of space, game designers and indeed players also impose their views into the spatial configuration of the game world. Finally, this line of analysis also allows one to glimpse into the symbolic associations and affective connections that players build when moving and interacting with the game world.

The Dwelling Perspective

Can video games be used to gain a better understanding of how people lived in the past? For many authors, the representational power of this medium can be productively used to go back in time, allowing people to 'travel' to past worlds. I believe that this potential remains at a very superficial level. Most historical games are developed as play spaces skinned to 'look like' a past reality but very rarely are imbued with the complex layers of meaning from historical worlds. While many existent games let us navigate and marvel with skillfully crafted environments, sooner rather than later we discover that these environments are nothing but theatrical backdrops populated by robotic agents with which we cannot establish any meaningful connection. Even in rich and highly interactive worlds such as Skyrim, this lack of meaningful interaction leads some players to become frustrated and to lose any sense of inhabitation:

"I finally realised the problem I was having with Skyrim: It felt soulless. I may as well have killed Agnis and taken her stuff, because what did it matter whether she was there or not? I suspected that nothing I did would ever matter, and that has been my experience as I've progressed through the game. Skyrim is a huge world drawn with a level of detail that entices us to lose ourselves there, and is filled with things to do, enough to keep us occupied probably for years. But it also feels empty and pointless." (Scimea 2011)

Although many other players may disagree with this quote, the sense of placelessness experienced by this particular player cannot be overlooked. In many ways, this feeling can be compared with the psychological emptiness of the main character of the film 'I Am Legend' (2007), a lone survivor of a planetary apocalypse, who makes hopeless attempts to simulate a social life in an empty world by deploying mannequins at various city spots.

What would be needed to overcome the present limitations of video games and to create a more complete sense of inhabitation? A strong referent to move video games in this direction can be found in Ingold's (2000) ideas on the temporality of the landscape. This author argues for an integrated study of the landscape according to the 'dwelling perspective'; a way to see the landscape as an enduring record of the transformative power of the people living within it, generation after generation. From this perspective, temporality and historicity merge in the experience of the people carrying on with their activities of everyday life. The unitary form of analysis is the task, the constitutive acts of dwelling, which Ingold defines as "any practical operation, carried out by a skilled agent in an environment, as part of his or her normal business of life" (Ingold 2000: 194–195). Mapped on top of the physical environment, this complex web of agencies conforms an analytical layer that Ingold designates as 'taskscapes'.

Although Ingold did not extend his theory to game or cyberspaces, his ideas can be legitimately exported and productively applied to historical games design, helping developers to construct interactive worlds perceived as inhabited spaces, not mere theatrical scenery devoid of social and cultural presence. Key to the production and implementation of game spaces as learning environments is the determination of their affordances, a concept introduced by Gibson (1979) in his ecological theory of perception. According to this theory, the interaction within the game world can be seen as a fine-tuning or sensitisation of the perceptual system of the player to particular features of the environment. The learning experience from this standpoint does not consist on the transmission of knowledge or experience, but on the setting up of situations in which the player is provided with the opportunity of exploring the game environment, discovering by him or herself the specific ways in which the salient features of the environment – game systems and/or other players – can be used or transformed in the context of play.

Designing an Anglo-Saxon Game

With the goal of investigating how games can be designed and used to foster the meaningful understanding of historical landscapes, I set myself the project of developing a historical game where I could test different design hypothesis. I decided to situate the game on the early Anglo-Saxon period of England, around the first half of the fifth century. The archaeological evidence suggests that at that time, Germanic tribes arrived to settle in this land, changing the culture, language, and establishing many of the towns and cities we are still able to visit today. Although this period is part of the national curriculum for Key Stage 2 in England and Wales, too often it does not receive an adequate level of attention across schools in the UK, resulting in a significant number of students leaving formal education with almost no knowledge of British history prior to AD1500 (Houghton 2016:13–14).

In very broad terms, the game prototype should convey a sense of everyday life in Anglo-Saxon time. Making a contrast with other games of historical persuasion, I decided to avoid the representation of violent conflict, often the main focus of commercial historical titles and mainstream media situated in this period. Games centred on combat and action are especially appealing to young audiences but this form of interaction tends to overshadow non-violent mechanics, which are left as secondary, at best. Also, I wanted to avoid as far as possible the action game 'genre baggage', described by Champion (2008: 223) as the tendency of importing patterns of interaction from action games into games with more educational aspirations, which manifests in players often more interested in destroying the objects presented in the scene rather than investing any time and energy learning from them.

From this very initial brief, the next step consisted in initiating the process of designing and building a functional prototype able to translate historical meanings into definitions of ludic and narrative interaction. Very often, historical game researchers at this stage opt for 'picking up' a suitable game genre from the list of existent games in the market, adapting the game mechanics and representational skin to better match the pedagogical goals or historical aspirations of the project. My contention is that this approach severely limits the possibility of moving the analysis beyond proven formulas and ready-made solutions. In opposition, I think that historical game design should be regarded as a 'wicked problem'; contexts in which the experimental attempts to solve the problem are often the only way to get a better understanding of it in first place. In cases such as this, many times the best thing to do is to roll-up the sleeves and build experimental game prototypes, informed by the analysis of previous games, to gain a better understanding of the design problem space (Mateas and Stern 2005).

But before delving into the modelling of three-dimensional worlds and the writing of thousands of lines of code, a number of critical decisions needed to be made. These decisions were in essence design specifications; key requirements that needed to be met in order for the project to succeed. What follows is a review of the most important points in the design specification of the Anglo-Saxon game project, briefly describing the considerations explored in its development.

Like any other medium, games can be designed to present historical knowledge from a particular disciplinary standpoint. I identify this as a historical approach, the first critical decision point in the process of designing a historical game. In this point, a major distinction can be made between the micro- and macro-historical approaches. While a macro-historical approach focuses on the long-term developments of historical continuity and change across large sections of population, micro-historians put the emphasis on the minute detail of everyday life of one or very few people, investigating it with an almost obsessive attention to detail. For macro-historians, the object of interest is to unveil the patterns of historical change, whereas micro-historians concentrate on elaborating thick descriptions of everyday life, discovering the underlying attitudes, conceptions, and modes of thought of historical agents.

Translated into video game form, both approaches constitute completely different design programs. Typically, a micro-historical game would privilege the use of a first or third person point of perception to control one or a very limited number of characters. In contrast, a macro-historical game would use a top-down or distant camera to perceive and navigate large sections of game space, allowing to efficiently control a number of agents. These specifications provide a first look at the implications that the selected approach will have in the following stages of development, highlighting the importance of making a commitment in an early phase of the project.

A second decision point in this project regards the definition of historical focus and perspective. Theoretically, a development team with enough time and resources can construct a game world of an astonishing level of complexity. Giving ourselves freedom to dream, we can imagine a world in which plants are not just two-dimensional billboards, but actually change in time, growing and showing real-world patterns and behaviours; animals of different classes roam freely through the environment; weather changes according to seasons, and a multitude of

Figure 1. View of the player's avatar in the Anglo-Saxon game world.

agents carry on with their independent lives. Although open worlds like this are becoming very close to be real in recent triple-A titles such as Grand Theft Auto (GTA), still games with this level of openness present a clear definition of who the player is, and what he or she has to do. Following the same principle, historical game designers need to make an early commitment in terms of the perspective and focus of the playing experience. Continuing with our GTA example, we could state–albeit in very simplistic terms–that this game focuses on gangster life from the perspective of an aspiring gang member. Undoubtedly, the experience that the game offers would be completely different if we change the perspective to be that of a policeman, or perhaps a normal citizen affected by gang crime.

In regard to the Anglo-Saxon game, after some initial prototyping I decided to concentrate my efforts on a micro-historical game, centred on everyday life, where gameplay and narrative could be experienced through the embodiment of a single character, a particular Anglo-Saxon individual–a powerful ealdormen (nobleman), ðegn (land owner), ceorl (free man), or slave–through whom the player could experience the life, problems, and limitations of the time (Figure 1).

The third decision point concerned the adherence of the project to specific theoretical models and data sets. In this sense, we regard games as simulations of past realities. Although we can easily establish distinctions between games and simulations, we can also agree that every game, even the most abstract ones, contains some sort of simulation, albeit with a varying degree of fidelity to a real-world source. This makes video games a privileged medium to communicate scientific knowledge about the past. As an example, the developers of the popular Sid Meier Civilization reportedly based the game's model on Paul M Kennedy's (1989) economic theory, presented in his seminal work The Rise and Fall of Great Powers: Economic Change and Military Conflict from 1500 to 2000. Likewise, we can concur that any historical game can be designed to convey theoretical frameworks, historical interpretations, or/and archaeological data, embedding this scientific knowledge into its procedural simulations and graphical representations. This view taps directly into procedural rhetorics, a paradigm that sees games as powerful persuasive devices, capable of conveying complex meanings about the world in the formal encoding of its procedures and rules.

In the Anglo-Saxon prototype, the procedural interaction is aligned to the idea of using the game as a mediation of historical taskscapes. For this purpose, a special emphasis was placed on making almost every object of world 'clickable'. Through the interaction with the mouse, players are able to access contextual information about the selected object, as well as a selectable list of its 'affordances'. This intuitive interface gives players the ability to perform a variety of tasks, some of which have a direct immediate effect, while others are part of a chain of tasks that needs to be performed until the end to have any measurable impact in the game. Every task was assigned a specific duration, which is required to reach its end to be performed. 'Waiting time', thus, is defined as the 'cost' or the 'currency' of the task. This idea mirrors Ingold's definition of the value of tasks as the unitary acts of dwelling: "Now if the value is measured out in units of money, and land in units of space, what is the currency of labour? The answer, of course, is time–but it is time of a very peculiar sort, one that must be wholly indifferent to the modulations of human experience" (Ingold 2000: 195).

Although through the execution of tasks players are able to develop a situated understanding of life in the harsh conditions Anglo-Saxon England, I would claim that the major educational potential of the historical game does not reside on its capacity to model the past with scientific accuracy. In this sense I agree with Nitsche (2008: 9) in that the most important function of video games is not to "provide new knowledge through the execution of their code", but to propose "engaging questions" and a dramatic experience that does not concentrate on the data, but on the player. While we can certainly gain a better understanding of the available data and theories about historical contexts by playing a game, this is something that we could also obtain from tinkering sliders in an interactive simulation. Games extend this function and reach their full potential as historical learning contexts when, instead of just giving players space to play and visualise data, they are designed in a way that drives them to care about the potential outcomes of their actions and decisions. This subjective engagement, and in some cases strong emotional involvement, is a characteristic that makes this medium distinct from other forms of historical mediation and offers multiple opportunities for its use in educational contexts.

With this idea in mind, I developed a series of characters in the Anglo-Saxon game. These characters have no manifestation or embodiment in the three-dimensional world but connect with the player through the game's graphic interface, offering a range of opportunities to explore conflicting aspects of culture through text-based conversations. Some of these characters are presented as "family members", who the player needs to feed and take care of (Figure 2).

Finally, and taking into account the educational motivation of this project, I introduced the decisional layer of pedagogical orientation. For this purpose, I took as a referent the historical pedagogies proposed by Seixas (2000): collective memory, disciplinary history, and post-modern history. 'Collective memory' supports the idea that it is possible to have a single, unified version of a historical account, concentrating efforts in providing students with the means to recall the 'best possible version' of the past; 'disciplinary history' aims to engage students on following the disciplinary processes and modes of thought of professional historians; and finally, 'post-modern history' concentrates on raising awareness of the critiques that post-modern thought does to authoritative versions of the past, providing a learning environment in which students build skill and confidence in navigating through multiple and sometimes conflicting versions of the past.

We could theoretically build our historical game to accommodate the requirements of any of the three perspectives outlined by Seixas, but arguably only the second and third perspectives make use of the full potential of games as historical learning contexts. It would be perfectly possible to design a game with the goal of leading the player through the 'best possible version' of the past, but this hypothetical game would most certainly have to nullify player participation and agency, both defining characteristics of the medium. This could be achieved by, for example, preventing the player from progressing unless she or he followed the 'correct path', but this type of game would most certainly restrict or completely disable player choice. Games can certainly remediate linear media, offering potential design solutions to the problem of deviating through alternative, 'inaccurate' versions of history, but, in my view, games work at their best when they present worlds that can be freely explored, traversing the multiple paths of navigation in a decisional space. Within these environments, players are allowed to construct alternative, non-authoritative, and even highly unlikely versions of the past, accessing the intricate web of causal connections encoded in the game algorithmic model. Manifestly, games constructed in this way have greater affinity with the "disciplinary" or "post-modern" historical pedagogies than the linear account proposed by "collective memory".

Figure 2. Dialogue interface with Vilburg, one of the family members implemented in the game.

Testing the Anglo-Saxon Game

After a sequence of iterations, the Anglo-Saxon game prototype is in its final stage of development. This version was tested in a primary school classroom, where data was collected following a pre-post test methodology. In the first session, children between 6 to 7 years old were asked to draw a picture representing life in Anglo-Saxon time. In the following sessions, the game was played by the children, collecting in-game data from their actions and navigation. Lastly, children were asked to draw a final picture communicating their ideas about the period. In both the first and final drawing sessions, mini-interviews were conducted with students, following a "talk and draw" research approach (Prosser 2007: 22).

Although the analysis of the data collected is still in process, the combination of drawings and mini-interviews proved to be revealing. This methodology provided an insight into children's previous historical assumptions and thoughts before and after playing the Anglo-Saxon game. Children were able to express ideas, emotions, and experiences often difficult to articulate in verbal language. In most cases, these ideas were expressed in the form of narratives, with the drawing's author assuming an active role within the representation. Indeed, when asked to explain certain aspects of the drawing, in most cases children situated themselves as part of the represented world, describing their actions and their relationship with the objects depicted in their imaginary historical setting. Through these narratives, children represented their understanding of the world, making sense of it both emotionally and factually while also defining their place in it.

In many ways, the personal narratives situated in this imaginary setting can be seen as acts of re-enactment, an affective form of historical encountering that has received an increasing amount of academic attention in recent years. When children concretise their ideas about Anglo-Saxon time in the form drawings, they are not just depicting a world detached from themselves; they 'inhabit' the representation through their narratives, which give evidence of personal ideologies and theories about the world. When questions were raised about their creations, children spontaneously explained their drawings as vivid accounts of a personal experience as had been 'lived' by them. Reading between the lines, these accounts are a rich source of explanation about 'the order of things', where assumptions about the present and the past often blend together. As an example, a child that presented himself as 'the best hunter' drew a village in which a house looked bigger and more elaborate than the rest:

Interviewer: Is this your house?
Student 1: Yes
Interviewer: Why is this your house?
Student 1: Because is the best house I drew in this picture

Interviewer: So you would be living in the best house?
Student 1: Yes
Interviewer: Why? Why you would be living in the best house?
Student 1: Because, I'm thinking that I am respected… Because, food was an important thing for the Saxons […] there was quite a bit but it was hard to get… and if you were a good hunter that means you would have more money from selling the food that you caught… and if you had family you were able to keep your family safe.

In this case, the child built a world in which his personal identity, as a result of a natural talent to bring food to the table and to the market, occupied a predominant position in the social ladder of his imagined Anglo-Saxon world. Similarly, children expressed assumptions about genre: "there were kings, but not queens"; violence: "they used to fight a lot and people got hurt a lot"; social life: "sometimes they meet on campfires to sing stories and tell stories"; and the hardships of everyday life: "life was very hard". Interestingly, by representing their thoughts in paper space, children also built an environment where the space was not seen as a neutral container of objects and artefacts, but as a defining factor in everyday life and the affordances of objects and artefacts. This can be seen in the following interview extract where the child drew campfires situated outside.

Interviewer: Why do you have a fire in there?
Student 2: I'm not really sure. They did have these fires in those days
Interviewer: They made campfires?
Student 2: Yes
Interviewer: Why did they make campfires? Maybe for cooking?
Student 2: Yes
Interviewer: And they are outside the house…
Student 2: Some can be outside, and some can be inside
Interviewer: Why do you think they made them outside?
Student 2: Mmm… I think the outside ones were more for… you know, like singing songs and getting together
Interviewer: I think that's important, and the ones inside were for?
Student 2: Cooking things

While playing the game prototype, these assumptions were very much present, and were revised in connection with the gameplay feedback. As an example, the difficulty posed by the game in finding or farming food and keeping all the family members alive was judged as "authentic", as it corresponded with the perception that "life was hard". In other cases, the game triggered a cognitive dissonance when it presented situations that challenged their previous assumptions about the period. As an example, the game presented an instance of a dialogue in which a family member called Vilburg–the son of the player's avatar–asked his father not to be sold as a slave in the case that the crops failed. This situation–not at all unusual in Anglo-Saxon time–was one of the few narrative scenarios remembered by all the children and provided an opportunity to extensively discuss the topic of slavery during a post-play session. Used in this way, the game became an 'emotional trigger', successful in concentrating the attention of most of the children in a particular historical topic.

Conclusion

This paper presented an overview of the development process of an experimental historical game prototype based on Anglo-Saxon England. In this development, Lefebvre's theory on the production of space and Ingold's ideas on the perception of the landscape were used as referential frameworks in the development of the game prototype and the design of its testing methodologies. Both theoretical bodies were continuously interrogated during the iterative development process and contextual implementation of the game in a primary school classroom, furthering the understanding of historical game landscapes and the processes of embodiment, incorporation, and expressive appropriation of the space. Initial testing in the context of a primary school classroom revealed that children's previous knowledge, assumptions, and naive theories about the past are being constantly interrogated by them while playing the game, resulting in dissonances that can be productively exploited to foster their understanding of the historical period.

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Databases and Collaborative Data Management

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Spacialist – A Virtual Research Environment for the Spatial Humanities

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Abstract

Many archaeological research projects generate data and tools that are unusable or abandoned after the funding period ends. To counter this unsustainable practice, the Spacialist project was tasked to create a virtual research environment that offers an integrated, web-based user interface to record, browse, analyze, and visualize all spatial, graphical, textual and statistical data from archaeological or cultural heritage research projects. Spacialist is developed as an open-source software platform composed of modules providing the required functionality to end-users. It builds on controlled multi-language vocabularies and an abstract, extensible data model to facilitate data recording and analysis, as well as interoperability with other projects and infrastructures. Development of Spacialist is driven by an interdisciplinary team in collaboration with various pilot projects in different areas of archaeology. To support the complete research lifecycle, the platform is being integrated with the University's research-data archive, guaranteeing long-term availability of project data.

Keywords: spatial humanities, virtual research environments, digital archaeology

Introduction

Nearly every archaeological project uses some kind of digital data management system. That could be a complex folder and file structure, a database system or a geographical information system (GIS). In many cases, all these tools are combined in more or less complex environments requiring a significant amount of maintenance. Usually, development, implementation and maintenance are in the hands of archaeologists often with limited knowledge of these information technologies. In our experience, such systems tend to be unsustainable because they lack a thorough requirements analysis and cannot make adjustments. Consequently, these environments will be very specific for a single project, and the reuse in comparable projects will be largely impossible without significant, often complex adaptations. The lack of a thorough and complete documentation as well as the frequent change of the responsible staff makes matters even worse. Thus, most new archaeological projects will start from scratch with a new system setup, repeating the same mistakes and facing the same issues over and over.

Furthermore, in most cases, reuse of data is also not intended, and projects do not have a data management plan to guarantee long-term sustainability and reusability of their data sets and analyses. Facing the downsides of these practices, many funding agencies (e.g., the German Research Foundation) have made data management and data archiving and sustainability plans mandatory for new research project proposals. As we observe in our daily consulting practice at the eScience-Center at University of Tübingen, researchers in the humanities are struggling to create such plans because of a lack of knowledge about methods and tools that support this effort during and after the project. The complete loss of data after a short period of time following the project's end can be observed in many cases.

In the last decades, a variety of projects tried to develop a data management system, aiming to solve the aforementioned problems with a single tool. Powerful tools like ARK (Eve and Hunt 2008), Heurist (Johnson 2011), and iDAI.field (Henze et al. 2013) were developed, but never widely accepted in the archaeological community. These comprehensive tools might be very useful for large projects with powerful IT support. In most archaeological undertakings, however, these systems would overburden the staff with too many ways of managing the data and complicated installation and maintenance procedures.

In 2009, the ArchGate project started with the aim to develop a modular digital research environment for small projects with limited needs and limited IT support (Lang 2012). Like the projects mentioned before, ArchGate was also never widely accepted by the targeted audience. We underestimated the heterogeneity of the archaeological projects resulting in constant project-specific adjustments, which were neither readily transferable to other projects nor contributing to the system as a whole. The main cause of this problem was a lack of abstraction in the data model, which was not flexible enough to store certain types of information generated by the researchers. We ended up with a wide range of different versions of the same tool with diverging data models, tables and functionalities, deployed on different computers. Since ArchGate was designed as a locally deployed Java desktop application, updates and patches had to be applied to every single ArchGate instance. We also underestimated the workload necessary to maintain all these instances, resulting in delays and dissatisfied users, which caused even more project-specific adjustments. After ArchGate ran out of funding most of our users simply did not have the financial capability nor the willingness to pay for necessary changes and updates to the system. Therefore, we decided to give up the tool and relaunch it under the brand name "Spacialist" based on the lessons we learned from ArchGate.

For us it was clear that we needed a higher degree of abstraction of our data model to manage all information recorded by the researchers, without requiring project-specific adjustments to deployed instances. Furthermore, we assigned permanent staff maintaining and updating the system in constant contact with the end-users to avoid common project-funding issues inherent in short-term research projects. After the project funding ends, a sustainable business model will be essential to guarantee the end-users a long-term maintenance of the system and their data.

The Spacialist Approach

It is evident that most archaeological projects have a set of common requirements and constraints related to collaboration, recording and editing as well as visualization and analysis of research data, including georeferenced information. However, many projects—even within a specific subdomain of archaeology—maintain highly heterogeneous sets of project-specific requirements. This heterogeneity can, for instance, range from simple labeling and language issues to more complex issues like different conceptualizations and organization of objects and relationships within the projects' (sub-)domains. Also, the set of features required for offering tailored tools for particular projects, work practices within a project team, and supporting these over the life span of a project as well as afterwards can vary significantly. While one project, for instance, might organize data using a stratigraphic organization like a Harris matrix, other projects might rely on a hierarchical taxonomy or geographic map as primary organization and interaction metaphor. The following two subsections are intended to set out the approach dealing with this heterogeneity in Spacialist while avoiding reinventing the wheel. This relates to the Spacialist project setup (Section 2.1) on the one hand, and the principles of the Spacialist software (Section 2.2) on the other hand.

Project Setup

A prototype of Spacialist is being developed over a two-year period in a publicly funded project through the eScience initiative of the state government of Baden-Württemberg, Germany. One of the keys to success of the project and thus obtaining a high quality of the software is an early and tight involvement of pilot project partners, who help provide the development team with functional requirements, feature requests and feedback (Derntl et al. 2015). To ensure a smooth communication between collaborating researchers and the Spacialist software developers, the

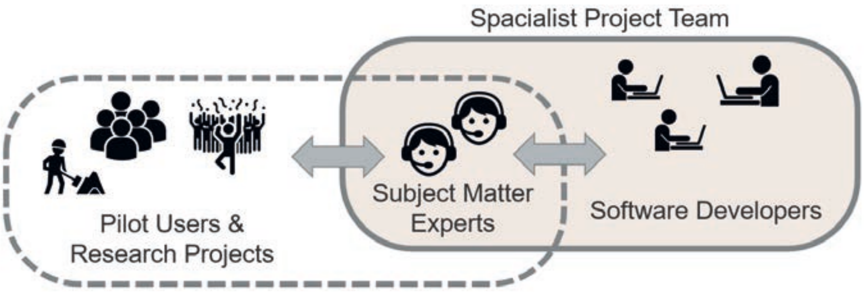

Figure 1. Project collaboration setup.

eScience-Center employs in addition two part-time subject matter experts – archaeologists with a strong computational background and field-work experience – as part of the project team to mediate and translate (see Figure 1). The whole project is coordinated by permanent staff.

To increase the visibility of Spacialist for research projects and to simplify participation for external developers, we rely on an open-source software strategy, which includes (a) the exclusive reliance on open-source libraries and frameworks, and (b) the commitment to publicly host a software repository on GitHub[1] under the MIT license[2], a strongly permissive open-source license. Moreover, most parts of the software process are openly communicated via GitHub milestones, releases, and issue tracking features. Any user may post issues, bugs and feature requests, and can get in touch with the developer team.

Technology Pillars

Learning from previous failures like the ones addressed in the introduction, we initially devised a small set of technological pillars that should later guide each and every technical decision in Spacialist. These pillars rest mainly on the principle of abstraction, which enables breaking down the complexity of a software system into levels that encapsulate certain system aspects and that build and rely upon each other (e.g., Vogel et al. 2011). The three pillars are:

- **Modular, extensible application platform**. In Spacialist a set of core modules can be combined and extended with add-on modules that are required or useful in a specific project. Spacialist is deployed as a hosted platform (either self-hosted or third-party hosted) on the web, and for each project a custom configuration of core and extension modules is instantiated to serve as the project-branded Spacialist application using a specific web address. The system architecture is described in Section 4.1 and the current ecosystem of modules is explained in Section 4.3.

- **Domain-independent, extensible data model**. The data model of the Spacialist core remains independent of any specific project or domain. It allows defining project-specific *context types* (representing any type of object, thing or entity in the project domain, e.g., a survey area or a find), their relationships, and the attributes that identify and describe individual instances of context types. The core data model can be extended by add-on modules. It is described in detail in Section 4.2.

- **Thesaurus-based domain representation**. Knowledge representation in all Spacialist instances is based on a simple, highly abstract representation of concepts and their relationships in the target domain of the projects. This allows hierarchical knowledge organization. This thesaurus-based approach is used both (a) for the labeling of user interface elements and (b) for the definition of project-specific context types, attributes, and value enumerations. The approach is described in detail in Section 4.4.

Application Cases

The development of Spacialist is driven and accompanied by a diverse range of research projects mainly from archaeology and cultural heritage. These

1 https://github.com/eScienceCenter
2 https://opensource.org/licenses/MIT

research projects have their own funding and have committed themselves to using Spacialist as a virtual research environment. This is a win-win situation in that it offers real-world application cases for the Spacialist team, while the participating projects benefit from tailored software modules and support. To get an impression of the kind of projects supported by Spacialist, we present two selected pilot projects in more detail.

Settlement and Society in Pre-Modern Oman

Large parts of the Sultanate of Oman are characterized by a mainly arid and hostile life environment. Less than one hundred years ago, before the modernization of the country in the second half of the twentieth century, sedentary live was mainly restricted to scattered oasis settlements of different shapes and sizes (Jones 2015). Oases formed microcosms consisting of various settlement and fortification buildings, infrastructure, date plantations and agricultural areas, as well as complex irrigation systems guaranteeing the survival in these environmental conditions. Archaeological excavations and remains of ancient monuments still visible on the surface point to settlement sites of the third millennium BC located close to modern oases, posing the questions of similarities or differences in site location preferences and adaptation to environmental pressure.

Such questions shall be faced by the recently initialized project "Settlement and Society in pre-modern Oman" – an interdisciplinary collaboration between the institutes of Islamic Studies, Near Eastern Archaeology and the eScience-Center of the University of Tübingen together with the Ministry of Heritage and Culture and the Ministry of Endowment and Religious Affairs of the Sultanate of Oman. The primary aims are (1) the examination and diachronic comparison between these two forms of subsistence separated by four millennia; (2) documentation of the abandoned mudbrick settlements by modern aerial and terrestrial scanning methods; and (3) conservation of knowledge about water and oasis management, which was passed on mainly orally over the generations.

These aims and the specific project setting come with several constraints and requirements, which guided the selection of Spacialist as the virtual research environment to support the entire project lifecycle. Some of the most important ones are listed below:

- A key characteristic of the Oman project is its multidisciplinary nature and the close collaboration with the local ministries and authorities allowing the combination of different methods and techniques from varying sciences. Such an approach may result in a broad and widespread understanding of the subject matter but also comes with some risks. Due to different methods, terminologies and data sets, the created information is often collected and stored by each party in their own databases and software environments, being only partly accessible by or portable to other partners, thus preventing direct and efficient scientific exchange. To avoid such problems, a collaborative tool for acquiring, storing and linking data based on standardized formats was required.

- A controlled vocabulary was required to allow translating labels for all used concepts and entities into different languages. This would facilitate the collaboration and exchange with local authorities in Oman as well as colleagues from around the world. The users can work in their familiar language without accidentally mixing up concepts.

- Since enormous amounts of various digital data are being produced and used within the research project, tools to upload, download, view and tag different data elements and sets like photos, scans, documents, geodata and 3D models were needed. This allows all partners to use these data without distributing them manually and using special viewers.

- The complexity of the involved sciences and the general subject matter makes it impossible to cover all possibilities in predefined data forms or controlled vocabularies. Therefore, an important requirement was to allow the creation and ingestion of new concepts over time, the reorganization and consolidation of the thesaurus, as well as the adaptation and definition of existing and new form sheets

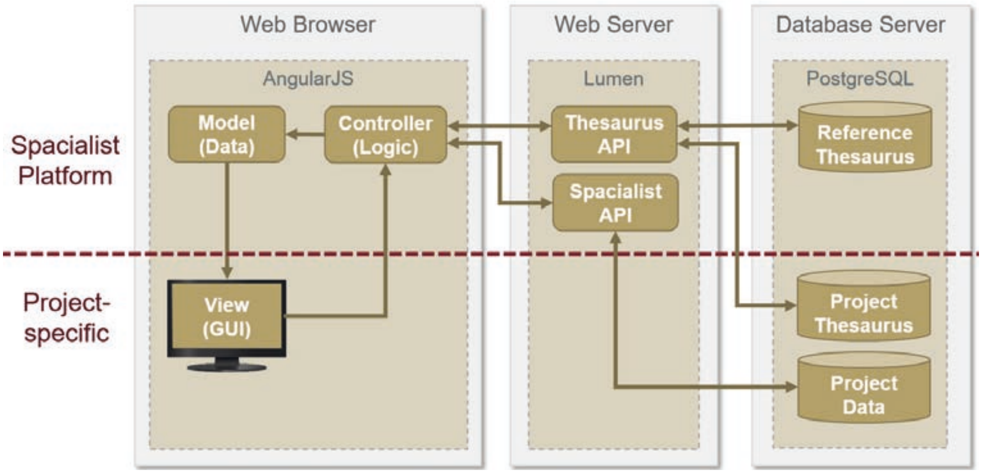

Figure 2. Spacialist layered system architecture.

to enter data, respectively, without requiring technical knowledge about operating a database system. This would make the project partners more agile and also facilitate later extensions and adaptations of the virtual research environment or the incorporation of new methods or approaches, for instance, in follow-up projects.

- The need to link data to a given concept (context or type) bundles all available information in one place. This allows internal researchers as well as external specialist to get much needed background information and to stay up to date.

Steinlachtal

The valleys of the Steinlach and Wiesaz Rivers, located in Southwestern Germany at the foot of the Swabian Jura, between the cities Tübingen and Hechingen, have a rich archaeological record. By using landscape-archaeological approaches one can try to reconstruct the ancient settlement structure and extract information from the record about how people have used and experienced the landscape. Due to its location at the foot of the Swabian Jura, the Steinlach river valley represents a transitional zone. First, a communication path alongside the Swabian Jura directs right through the valley. Second, the Wiesaz valley represents one of several valleys, which represent a possibility to enter the plateau of the Swabian Jura. In this context, the "Steinlachtal" project was set up to investigate the development of this cultural landscape from the Neolithic until the Iron Age and to analyze the systems of communication used over this time span.

The project has several key requirements for a software-based solution to data management:

- While the research of transport and communication in medieval times could use many different sources, landscape-archaeological approaches for pre-Roman times are mainly based on spatial data, originating from archaeological fieldwork. Therefore, tools were required that could handle geospatial data in a manner that suits archaeological surveys, which requires establishing a stratified system of research contexts from survey site to single find.

- Once the data are collected, one must be able to extract information about the settlement structure, transport routes, preferred places for burials or empty spaces, which were never populated. In comparing the results obtained for one specific period with another, it could be possible to see social dynamics (e.g., moving from the valley ground to the top of hills in unsecure times). Therefore, software with strong support for data analysis and visualization was required.

- To support the research workflow, a high interoperability and the use of accepted standards was desirable. This requires a research environment that not only offers possibilities for collecting (frontend) and storing the data (backend), but also features for extracting the

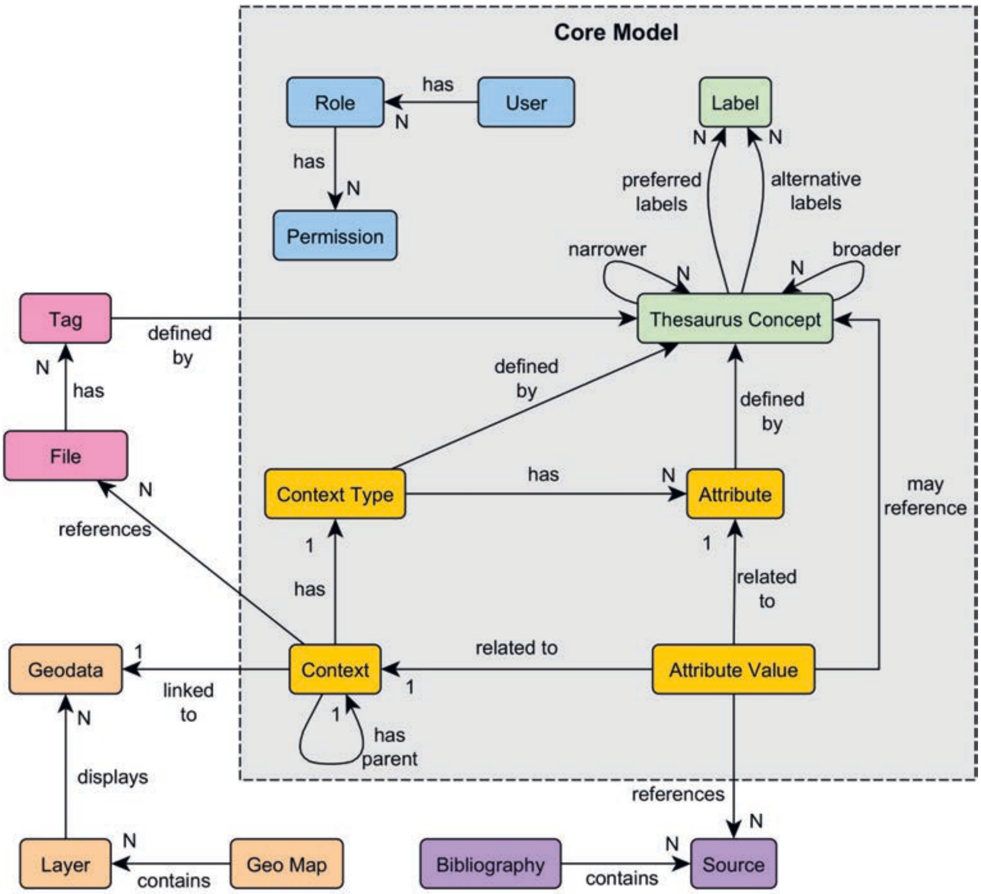

Figure 3. Spacialist data model illustrated as a simplified concept model. The core part is contained in the gray box. The extension parts are outside of the gray box and explained in Section 4.3.

data in standard formats to work with other specialized software for further analyses, e.g. statistical tools like Excel, SPSS or R and spatial analyses in geographical information systems like QGIS.

Spacialist Implementation

System Architecture

Spacialist was built as a web application based on a strictly layered 3-tier architecture separating the client that runs in the web browser, the application programming interface (API) that is exposed by a web server, and the database which is managed on a database server (see Figure 2). The components within these layers build exclusively on open-source tools and frameworks.

The frontend is written in HTML and JavaScript, which allows us to implement an interactive user interface. We use Google's AngularJS framework[3] for most of our JavaScript code, which implements the Model-View-Controller (MVC) (Timms 2016) design pattern to allow separation of concerns when dealing with data, application logic and user interface. This strict separation would even enable third-party vendors to build custom client applications that employ the Spacialist service layer. To simplify the service layer code and for the sake of easier maintenance we use the PHP framework Lumen[4], which can be used to implement RESTful APIs (Masse 2011).

On the backend, all data is stored in a PostgreSQL database[5], which we chose because of its long-standing tradition to adhere closely to the SQL standard. The PostGIS plugin[6] enables the database to support all known spatial reference systems as well as spatial, geometric and geographic objects. This plugin offers full support for geospatial processing and analysis and can also handle virtually any standard format

3 https://angularjs.org

4 https://lumen.laravel.com/

5 https://www.postgresql.org/

6 http://postgis.net/

Attribute Type	Description and User Interaction
string	Text input field
stringf	Textfield for larger strings (e.g. descriptions)
integer	Text input restricted to whole numbers
double	Text input allowing numbers with decimal digits
string-sc	Single-choice dropdown using ThesauRex references
string-mc	Multiple-choice dropdown using ThesauRex references (e.g. tags)
epoch	Combination of year range (e.g. 500 BC – 200 AD); also supports single-choice dropdown for specific era (e.g. Iron Age)
date	Date picker with popup
dimension	Combination of dimensions (length x width x height) and a unit (mm, cm, m, etc.)
geography	Geographical coordinates; can be entered either using WKT or a map popup
percentage	Slider with a range from 0 to 100%
context	A reference to another (existing) context; offered in a dropdown box

Table 1. Currently supported attribute types.

for geodata like GeoTiff, GeoJSON, WKT, KML and many others.

Data Model

As indicated earlier we designed a generic, shared data model that has to be used as a metamodel by all Spacialist project instances. The core of the data model – represented by the gray, dashed-line bordered box in Figure 3 – results in the abstraction that we consider each entity, concept or object within a project domain as a *context* (e.g., the Birkat Al Mouz oasis in the Oman project or the *Silexklinge* (flint blade) find in the Steinlachtal project). Each context can have any number of child contexts, which allows the building of a tree-like hierarchy of domain data (see Figure 4 for an example where *Silexklinge* (flint blade) is child context of the site *Öschingen*).

Each context is of one specific *context type*. The set of context types and their relationships in a project is defined by domain experts (usually the researchers on the project). Each context type consists of a set of *attributes* that are shared by all contexts of this type and capture the contexts' characteristics. Each attribute has a particular value domain, which is defined by assigning one of the available attribute types (see Table 1).

The labels for context types, attributes and enumerated attribute values each reference concepts in the thesaurus that define their localized labels. In the Oman project, for instance, an oasis is described by attributes name (text), type (enumeration), description (text), dating (date range), note (text), and its location (geography). When the researcher creates contexts during the use of Spacialist, each attribute of the context can be assigned a particular *attribute value*.

Multilingualism is achieved using the project thesaurus (see Section 4.4). Labels for context types, attributes and enumerated attribute values each reference concepts in the thesaurus that define their localized labels.

Application Modules

The core data model described above provides the basis for the core functionality of Spacialist, which is implemented in the main application module – the **Context Manager.** This module offers a graphical user interface to create, edit and remove contexts during the project work. The contexts are organized in a tree structure, as depicted by example of the Steinlachtal project main screen in Figure 4, left hand column. When a context is selected in the tree the main screen displays a form to describe the context using the attributes associated with the context's type. For instance, in Figure 4 the Silexklinge (flint blade) context, which has context type Fund (find) was selected and the list of attributes associated with this context type is displayed in the main form. By selecting the star icon next to an attribute's label, the

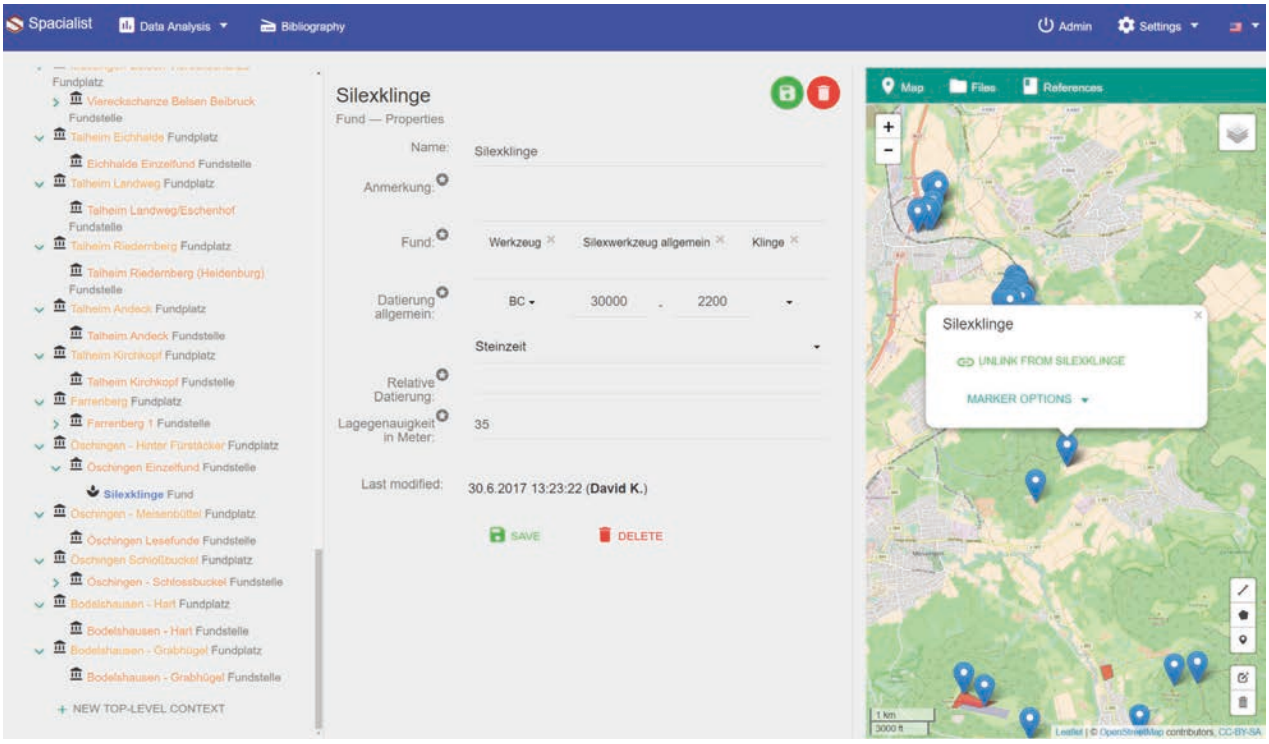

Figure 4. Screenshot of Spacialist instance main screen for the Steinlachtal project.

user can add comments related to the attribute value provided in the main form.

Pivotal for collaborative projects is the **User Manager** module, which is deployed as part of the Spacialist core. Upon each database request, this module checks if a user is logged-in and whether the logged-in user is allowed to invoke a particular request on the service layer, which translates to privileges for adding, updating, and deleting records in the database. User management is implemented using principles of role-based access control (ANSI 2004): Each user can be assigned to one or more roles, and each role comes with a set of permissions (cf. the blue shapes in Figure 3). Each user is then allowed to perform an action, if they are assigned to any role that comes with the necessary permission for the requested action.

All additional functional requirements need to be implemented through extensions of the Spacialist core. This is achieved through add-on modules. Each module may be equipped with a data model that extends the core model, a set of backend services for data processing, and graphical user interface components that implement and offer some well-defined functionality. In the following we describe the existing set of add-on modules.

As a virtual research environment for spatial humanities, Spacialist stores geographical data and allows working with those in the **Geo Map** module. Using PostGIS, all geodata are stored as (multi) points, (multi)linestrings and (multi)polygons within the project's specific spatial reference system. The model is extended to store geo-objects, but also modifies the context database structure. It adds a column for referencing to a specific geo-object. Thereby, it is possible to link each context to a geo-object (see the orange shapes in Figure 3). To interact with these geodata, a map view is added to the user interface that is implemented using Leaflet[7]. When the user selects a context in the Context Manager, its associated geo-object is activated on the map and vice versa. In Figure 4, the geo map is displayed in the right-hand column. Leaflet supports a wide range of map tile sources as base maps, most notably Google Maps, Bing Maps and all kinds of WMS layers[8]. The project administrators may add as many tile map providers as needed by entering the required parameters to fetch the map tiles. Overlays from Web Map Service (WMS) (Geographic information/Geomatics 2005) compliant service endpoints may be added to the map as well. For instance, in the Oman project

7 http://leafletjs.com
8 http://www.opengeospatial.org/standards/wms

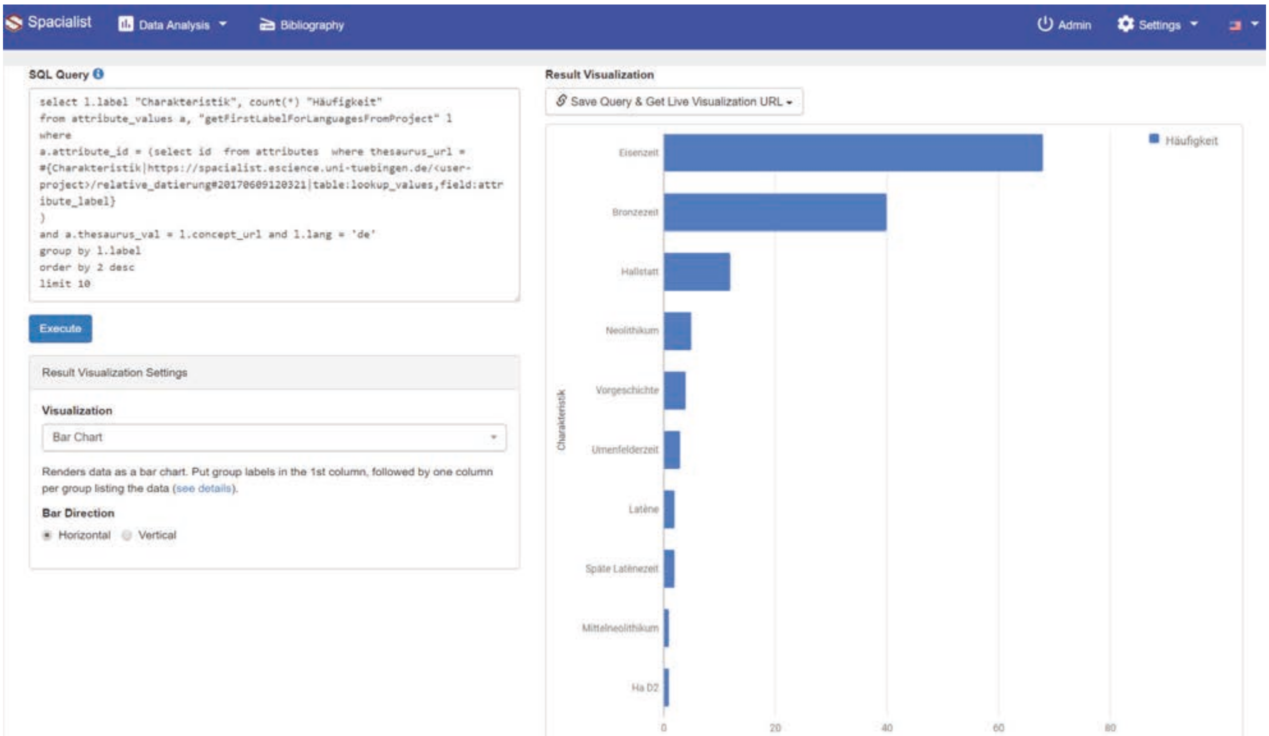

Figure 5. Analysis editor user interface of the data analysis module.

the aerial imagery of the target area was obtained using a high-resolution camera equipped UAV; the resulting images were processed, and the map tiles are now served by our GeoServer[9] via its WMS service. On the map, the geo-objects that reference a context location can easily be modified or deleted. It is also possible to add new markers and geometries on the map (see the edit controls in the bottom right corner of the map in Figure 4). A snapping feature helps to align new edges and vertices of geo-objects with existing ones on the map.

A **File Manager** allows end users to upload and view files, edit their properties, and assign them to contexts (see Figure 3, pink shapes). The add-on extends the core data model by adding a database table to store the relevant file information, amongst others the file URL, modification date and mime type. The file manager also supports the assignment of tags to files. Those tags are used for example to filter files by matching one or more tags. These tags are defined in the controlled vocabulary as part of the project's domain representation (Section 4.4). To simplify file handling, Spacialist can display different file types directly in the browser. This includes 3D viewer files, PDF, markdown, images, audio and video.

9 http://geoserver.org

Spacialist supports bibliography management through the **Bibliography** add-on. The bibliography is stored in a BiBTeX-like (Patashnik 1988) structure directly within the project database. Beside recording entries by hand, end users can import BiBTeX files from other bibliography management tools. Similar to the file manager, this add-on extends the data model to store bibliography data and links to core Spacialist data: each attribute of any context can be associated with references to sources contained in the bibliography (see the purple shapes in Figure 3). The add-on also adds a view to the interface which displays a list of references for selected contexts.

Finally, the **Data Analysis** module allows project team members to formulate queries and query templates to produce data visualizations. As depicted in Figure 5, the analyst enters a parameterized SQL query in the query box and then selects a result visualization which defines how the query result table shall be transformed and displayed to the researchers. Currently the module supports table, bar chart, ankey, timeline, candlestick, map and social network visualizations. Figure 5 shows a query that produces a bar chart with most frequent values for a given attribute. Each query can be stored as a template in the database. The researchers can retrieve any of these

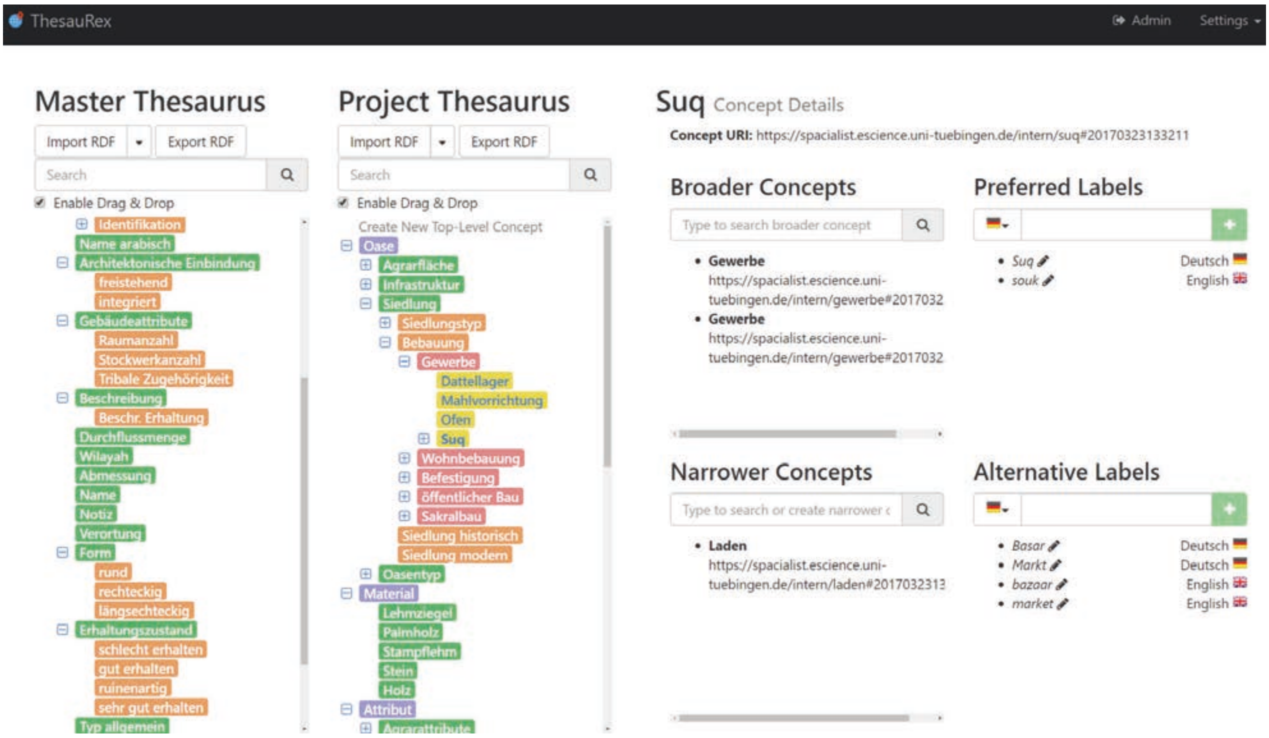

Figure 6. ThesauRex main screen.

stored queries, which will present them with the visualization of cached or live data.

Thesaurus-Based Knowledge Organization—ThesauRex

Employing a thesaurus-based knowledge organization is one of the technical pillars of Spacialist. To increase interoperability and simplicity of use by researchers and domain experts, we decided to adopt the Simple Knowledge Organization System (SKOS)10, a W3C Recommendation first published in 2009. After experimenting with existing thesaurus tools that support SKOS, we found that open-source tools are rare and come with little or no active support. Some proprietary solutions worked well (e.g., the PoolParty Semantic Suite11), but it would have been expensive to buy after the evaluation phase and there was no way to adapt such proprietary tools to specific needs of thesaurus modeling in Spacialist. Therefore, we eventually decided to implement the required subset of SKOS in a tool we called **ThesauRex**. The following description focuses only on those SKOS parts that were implemented in ThesauRex because of their immediate relevance to Spacialist. *Concepts* are the fundamental element in SKOS. A concept can represent basically any entity, object, idea or other item in the domain that is being modeled. They are identified by Uniform Resource Identifiers (URI) and can be labeled in different languages. SKOS supports different types of concept label, most importantly *preferred label and alternative label*. Each concept can have at most one preferred label per language, and the preferred label is used to present the concept to users (e.g., the traditional Arabic market as "souk" in English and "Suq" in German). To allow representation of synonyms, acronyms, abbreviations and other possible labels each concept can be assigned any number of *alternative labels* in any language. For the previous example, alternative labels in English could be "market" or "bazaar" and in German "Markt" or "Basar". The use of alternative and preferred labels offers effective multilingual support also for international collaborations or work groups that have differences in labeling concepts in their domain, which is quite common in many sciences, including archaeology.

To allow organizing the project's knowledge domain, SKOS allows relationships between concepts

10 https://www.w3.org/2004/02/skos/

11 https://www.poolparty.biz/

to be expressed. Any two concepts can be linked using the relationships *broader* and *narrower*. These can be used to represent a graph-based hierarchical knowledge organization. Through transitivity, a graph of *broader/narrower* relationships among concepts can be established. The project vocabularies are structured collections of individual concepts that are representing real world objects, including subjects of research as well as their properties and relationships. These relationships are represented within ThesauRex though an expandable tree structure established by the broader and narrower relationships (see Figure 6). Tree structures are simple to construct from broader/narrower relationships, easy to manage, and arguably more familiar to use and navigate for end users than network structures. In case a concept has a narrower relationship with multiple other concepts, it is displayed as child concept of all these broader concepts.

A unique feature of ThesauRex is its ability to work with not only one but two vocabularies (*cf.* the two concept trees on the left-hand side of Figure 6). While the project-specific vocabulary can be modified by the individual project to satisfy their requirements, the second one may be used as a reference for dragging and dropping parts of the represented knowledge into the project thesaurus. This enables the reuse of domain knowledge within and across research projects. In teams and organizations, the reference thesaurus can also be used as a private or public master thesaurus that is built and refined incrementally and reused by research projects. Both thesauri can be exported and imported via SKOS-compliant RDF files. Therefore, ThesauRex can also be used as a general-purpose, standalone editor for controlled vocabularies, although it was originally designed to be used together with Spacialist to generate and evolve project thesauri.

The experience so far with research projects that use Spacialist reveals that establishing a working data model based on Spacialist's abstract concepts is the most challenging initial task. This task typically requires several working sessions face-to-face between Spacialist team members and the project's researchers to achieve a common understanding of the problem domain and to be able to represent the domain using a SKOS-based thesaurus. For first-time Spacialist users, the initial, agreed project-specific data model is typically implemented by one of the Spacialist experts using ThesauRex. Even for complex domains that include several hundred concepts this can be achieved in less than a day. Previous collaborations with the projects mentioned above have demonstrated that later refinements of the data model, e.g. adding a new context type, or introducing an additional attribute to a context type, or extending the thesaurus for controlled-vocabulary attributes, can usually be performed by the researchers themselves in ThesauRex and Spacialist's data model editor without requiring extensive support.

Conclusion and Outlook

Based on the experiences made in the failed predecessor project ArchGate, it was possible to implement an operational prototype within the first months of the project. This first version is now used in four different research projects. The direct feedback from the researchers using the tool were extremely helpful to implement new functionalities and modules within Spacialist and to adjust the workflow to the needs of the users. The modular structure of Spacialist, the domain-independent data model and the thesaurus-based domain representation facilitated the setup of new projects, which can be done now in a few hours. In addition, adjustments and supplements can be made easily by the researchers within a web interface.

So far, Spacialist has limited data-analysis functionalities. These need to be developed in a next step after a critical mass of research data from the participating projects is available. Another important task will be further integration of the system into the research data repository of the University, so the whole research process from the recording up to the archiving of the data can be covered within a single toolkit. Furthermore, a mapping of reference models like in the CIDOC CRM ontology (ISO 2006) for cultural heritage documentation[12] should be created to guarantee the usability of the data in superior infrastructures.

One of the most challenging, ongoing tasks is the deployment of a sustainable business model, which will allow the long-term operation and the maintenance of Spacialist. To prepare for the transition to

12 See also http://www.cidoc-crm.org

a self-sustaining business model after the project funding ends, Spacialist is already being tightly integrated into the research data management consulting offers that the eScience-Center at University of Tübingen offers to its researchers. The long-term sustainability relies on a minimal set of services to be offered by permanent staff of the eScience-Center. These initially free services include consultation and analysis of the project plan or status, deployment of customized test instances to research projects, and hosting and maintenance of these test instances on University servers. Additional consulting services, long-term hosting commitments, and in particular the development of more complex data models and new project-specific features, are offered as premium services. In most cases currently this means that costs incurred by such services are included as part of the work plan and budget in new project proposals that intend to use Spacialist to manage research data.

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Improving Data Quality by Rules: A Numismatic Example

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Abstract

The archaeological data dealt with in our database solution Antike Fundmünzen in Europa (AFE), which records finds of ancient coins, is entered by humans. Based on the Linked Open Data (LOD) approach, we link our data to Nomisma.org concepts, as well as to other resources like Online Coins of the Roman Empire (OCRE). Since information such as denomination, material, etc. is recorded for each single coin, this information should be identical for coins of the same type. Unfortunately, this is not always the case, mostly due to human errors. Based on rules that we implemented, we were able to make use of this redundant information in order to detect possible errors within AFE, and were even able to correct errors in Nomimsa.org. However, the approach had the weakness that it was necessary to transform the data into an internal data model. In a second step, we therefore developed our rules within the Linked Open Data world. The rules can now be applied to datasets following the Nomisma.org modelling approach, as we demonstrated with data held by Corpus Nummorum Thracorum (CNT). We believe that the use of methods like this to increase the data quality of individual databases, as well as across different data sources and up to the higher levels of OCRE and Nomisma.org, is mandatory in order to increase trust in them.

Keywords: data quality, SWRL, uncertainty

Introduction

As is reflected in the title of this paper, our work has concentrated on the field of digital numismatics. The field already has a long history, and involves dealing with legacy systems and data that were often compiled over many decades by many different authorities. The challenge, then, is how to adopt and make use of new approaches such as Linked Open Data (LOD) without compromising existing systems. Consequently this paper also reflects our experiences in applying LOD in this context. For most of the issues discussed, solutions exist, but changing or rebuilding legacy systems to optimise them is in most cases not an option.

Data quality is often not felt to be as important as we think it should be. For many, especially managers, the addition of 100 new datasets sounds far more impressive than eliminating 20 errors. For example, in one case that we encountered, those entering data on coin finds into a national database were aware that they had six (!) different ways of entering the name of the Roman emperor Caligula, which severely restricted the validity of search results. Yet for a long time no effort was taken to rectify this despite the fact that the proprietary software being used very much simplified the use of standard vocabularies. But the truth is that, without knowing further details, it is impossible to decide which of the two tasks, adding 100 new datasets or eliminating 20 errors, would be more difficult or take more time. However, in our experience, we can state that dealing with data quality can sometimes bring very useful, if unforeseen, benefits. This is epitomised in a statement by Thomas Carlyle (1795-1881): *"Do not be embarrassed by your mistakes. Nothing can teach us better than our understanding of them. This is one of the best ways of self-education."*

Currently many archaeologists have their own datasets, and these are what they trust. But how often are these data checked for mistakes or inconsistencies? How can it be done? How is it possible to ensure that no dirty data gets into a system? With new approaches like Linked Open Data (LOD) (Berners-Lee, 2006), data are becoming publicly available, and the question arises as to whether these data are always consistent and how this can be checked? Our approach is to define logical rules and implement them in a corresponding system in order to allow automated testing. These tests could function as a gatekeeper before allowing data to enter a system, or as a regular check performed after a certain timespan. However, this method will, of course, only find errors for which there are rules. Furthermore, the focus of this paper is on detecting errors and not on their correction, which is a much more complex and difficult matter.

Why is this important? Because data are used to confirm or reject hypotheses. If data are incorrect, or inconsistent and messy, this could lead to incorrect results. A second hypothesis may be based on the first one, and when errors are discovered then the entire hypotheses based on the first one are immediately invalidated. This does not necessarily mean that the hypothesis actually was in any way invalid, but people may no longer trust it (or the person who proposed it). In a Big Data approach, it could be claimed that masses of data are used in order to overrule such errors statistically. Unfortunately, this is not always true, and in the case discussed we do not even have the necessary mass of data (of a stable quality). In the domain of archaeology, with many uncertainties and lost information, good data quality is required to ensure that at least the facts that are taken into account are correct.

What is more, with the LOD approach errors may get copied, replicated, or multiplied. Once this has occurred, rectification becomes ever more complicated. In an ideal world this kind of error propagation would not be dramatic, for systems would simply link to the LOD content and once the error is removed the problem would be solved, except in those cases where the link was made based on the erroneous data. However, LOD is open and used in various ways, and in many cases the provenance link to the source information gets removed or is omitted, so that correcting the LOD will not automatically correct the other systems.

The Current Situation in the Field of Numismatics

Since coins are a mass-produced medium, with more or less standard core data, compared to other categories of material culture, it was relatively easy to define and set up discipline-specific and stable digital representations of the concepts needed for the numismatic field. These representations take the form of HTTP URIs that promote worldwide interoperability between numismatic resources by providing access to reusable information about the concepts, as well as links to and from other fields of study. This way it follows the LOD approach, and also provides its own ontology. But while the work may indeed have been "relatively easy", it must nevertheless be stressed that the *Nomisma.org* project has already taken seven years to deliver the present volume of LOD concepts and that the work is still ongoing.

Projects can provide their descriptions of numismatic objects using the *Nomisma.org* ontology and the modelling described there (Nomisma.org, n.d. b). These data sets are then published by web projects that are based on *Nomisma.org*. By December 2018, such websites were publishing data sets from 33 institutions containing more than 280,000 descriptions of coins, coin types, and finds of various kinds.

For certain fields of numismatics, there are widely established typologies. This is especially true for the Roman Imperial Coinage and the Roman Republican Coinage, as well as for the coins issued in the name of Alexander the Great. For these, digital type corpora are already online, namely: OCRE (Nomisma.org, n.d. c), a digital type corpus based on Roman Imperial Coinage (RIC), CRRO (Nomisma.org, n.d. a) based on Roman Republican Coinage, and PELLA (Nomisma.org, n.d. d) for the coinage in the name of Alexander. All these online resources use the *Nomisma.org* ontology, and make use of the data sets submitted via *Nomisma.org*. Thus, where a coin from

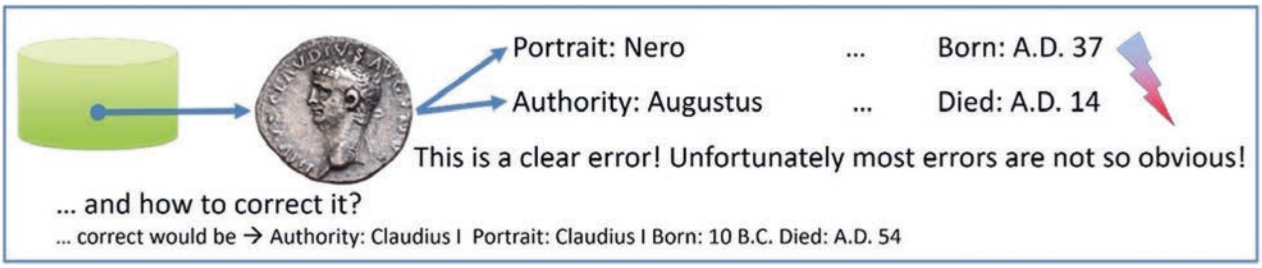

Figure 1. An example of a clear logical error of the kind that generally cannot be corrected automatically.

one of the data sets that employs the concepts in *Nomisma.org* is linked to a specific coin type in one of the typologies, it is listed in OCRE, etc. as an example of the type.

In a *relational* coin find database, some of the coins will be well preserved and easily identifiable, and so can be easily linked to an existing type corpus such as OCRE. In this case, the link to OCRE would be enough to specify information such as the authority, legend, mint and other type-relevant information, and the individual data on these need not be entered separately into the relational database. However, there are coins that are not so well preserved, and which cannot be attributed to a specific type, and for these it is necessary to store all the type-relevant information separately. When the data are analysed, it will be necessary to include all of this information, and if it has not already been done, it will be necessary to import the relevant information from OCRE. For this reason, many relational databases also store the type-relevant data for coins even where a link to the type in OCRE, etc. exists. This is partly due to the fact that normally several different type corpora have to be dealt with, and it is undesirable to reproduce them all within a database. The result is redundant information, something that normally should be avoided for it means that there is more than one place in which the same information is stored; and when later it is changed in only one place, the information will no longer be consistent. This is the case described here: on the one hand there is the link to the type corpora with its type-relevant information, but at the same time the same information is stored separately in the database. But where provenance information for the data is stored, it is possible to build systems in a way that keep track of the data and ensure consistency across them. However, in relational databases this does not come for free, and would need to be implemented.

In addition, many databases have legacy data, dating back to before the existence of OCRE, CRRO, etc. When the data were created, it was normal to store the type-relevant information in the individual coin records. But if a link to the new type corpora such as OCRE is added, redundant information is generated. However, in this case redundant information can also be useful, because once it is known to be redundant, it is possible to test if it is identical, and therefore if it is consistent. If it is not, then there is an error that has to be corrected. This is very similar to a checksum for IBAN numbers, etc. As defined in the next section, many rules are based on such redundant data.

It should also be noted that such checks not only ensure data consistency within a database, but when data are checked against other projects, this sometimes leads to the discovery of errors within external projects. With widely used LOD resources, such errors can result in exponential replication. In several cases we have identified such errors in the course of our work: the Portable Antiquities scheme at the British Museum had linked a late Roman mint to a town of the same name in a different location, while within *Nomisma.org* the apparent copying of blocks of text from one entry to another, without changing relevant individual elements, had resulted in the wrong dates being given for a Roman emperor.

Defining and Testing Rules

Rules are categorised here in two groups. Those based on redundant data, as described in the previous section; and pure logical rules, such as conflicts in the time line. A simple example for a logical rule could involve a coin showing a portrait of a different person to the issuing authority, such as a coin struck by an emperor for another member of the imperial family. When the person in the portrait is known to have been born after the death of the authority,

ID	Name	Description	Type
1	Issuer-Chronology	The production time span of a coin must fall within the reign of the assigned authority.	logic
2	Issuer-Portrait-Chronology	The person in the portrait must be born before the death of the authority.	logic
3	Denomination-Material	The denomination implies the material used (there could be exceptions to this rule).	redundant
4	Min-Max-Diameter	In case minimal and maximal diameter are provided, the minimal diameter should be smaller or equal to the maximal diameter.	logic
5	Date_From_To	The production period is normally given by the years defining the start (from) until then end of production (to). These two need to have the correct order.	logic
6	Compare_Types_Local	All coins within the database linked to the same coin type, should be equal with regard to the type-relevant information.	redundant
7	Compare_Types_Remote	The locally entered information should be equal to the type-relevant information provided remotely by a type corpora.	redundant
8	Weight	In many cases the weight of a coin is related to the material and diameter. However, since the thickness is generally not recorded for ancient coins, weight comparisons would provide no more than an indication. Coins of the same material and same diameter should be similar, that is within a defined rage. In addition, the condition of a coin has an impact (e.g. corrosion).	logic

Table1. A high-level description of some of the rules we defined. In reality, some of the rules were divided into a number of sub-rules and additional issues checked that are not mentioned in the description of this table.

there is clearly a time line conflict. Without a time machine, this would simply be impossible. Such a scenario is visualized in Figure 1.

Table 1 shows some examples of the rules at a high-level of description that we implemented and used. Some rules are further divided into sub-rules, and may take into account additional issues that are not part of the description in the table. Some of these need to be fine-tuned according to individual cases. For example, rules 6 and 7 depend on the type system being used. Many existing type systems define type-relevant information, and this information should be equal for all coins mapped to the type. However, what exactly must be equal depends on the type system, which means that the rules need to reflect the rules of the type system, and cannot be written for all type systems at once. There are even less rigid approaches to defining type systems (González-Pérez C., 2012), which would mean that a simple equal function would not be appropriate.

For the logical rules in Table 1 in particular, if they are not met there is clearly an error. An exception to this would be the rule on weight, which could require that two coins of the same material and similar diameter should have a similar weight (but this would not take into account that the thickness of coins can vary, information that is normally not stored, at least not for ancient coins). However, there could be various parameters that have an influence on the weight, for example: corrosion, wear, special treatment such as clipping or halving, and fragmentation. This makes it more complex, and in cases where the rule is violated, it might not automatically mean that there is a real inconsistency. There might just be a special case that is not represented in the rule so far. Here again, type corpora like OCRE can provide an indication of probability, as they provide the ability to retrieve information on the average weight and weight span based on the specimens linked to them.

An additional complication is uncertainty. In the AFE database, most fields can be marked as uncertain, in order to accommodate cases where there is missing or lost information, and this could therefore be classified as epistemic uncertainty. This is something that each rule needs to be analysed for; whether such an uncertainty flag can have an impact. Other fields provide the possibility of creating multiple entries for cases where it is not certain which of the entries the coin actually corresponds to; but at present no uncertain information of this kind is exported in our dumps to *Nomisma.org*. Other databases might not even allow such granularity. We have proposed ways of modelling uncertainty as LOD (Tolle and Wigg-Wolf, 2015), but this is an ongoing discussion. On top of this, each model reflects an abstraction, and this is true for relational models for the way data are entered via the graphical user interface, for the underlying model (ontology) for LOD, and even in the mind of each domain expert. In each of these models, and in the mapping between, bias and uncertainties can be generated that go beyond epistemic uncertainty.

With regard to geo-positioning, there is an ongoing discussion within the *Nomisma.org* steering committee. Each system has a different approach to dealing with findspot coordinates. The problem is that publishing the exact coordinates of a coin find in a publicly available environment like OCRE, could lead to plundering of the findspot by illegal detectorists. For this reason, different approaches are used when the data are published online. One possibility is to reduce the precision of the coordinates, for example by cutting off the last digits or, as is done for AFE, to only publish online the centre of the area or administrative unit where the findspot is located. For this purpose, a hierarchy for location information was set up within AFE. For online publication there are four levels of administrative units comparable to those provided in Geonames.org: federal state, county, parish, parish division. This means that the exact information on the findspot (most accurate) and the site (less accurate), which is required for scientific analysis, is stored locally and is not released as part of the LOD published under *Nomisma.org*. Therefore, rules addressing or requiring the most accurate geo-positioning cannot be applied to the LOD.

However, for coin finds, accurate geo-positioning could be one trigger for identifying duplicates between different datasets. For example, AFE and KENOM (KENOM, n.d.) contain overlapping data from literature that was manually entered into both systems. At present, at least the known cases are handled by indicating them in the LOD data: we included *skos:exactMatch* fields for AFE data in order to store this information and to export it into the LOD we provide.

Some AFE-specific rules for geo-positioning were set up within the AFE database, whereby the geo-data for the findspot was checked against the geo-data for its upper level (i.e. administrative unit), in order to see whether they correspond, or the findspot should, for example, instead be attributed to another administrative unit (a problem particularly for common names such as Neustadt). During these tests many errors were discovered, especially for one particular federal state. We realised that there had been an administrative-territorial reform for the federal state that was not reflected in our data. This is a significant problem due to the necessity to remain up-to-date. But because in the literature, which is often used when entering data into the database, there are references to the old administrative units and areas, it is important that this information is not deleted. However, storing and maintaining the evolution of the administrative divisions would be a project in itself. Even *Geonames.org* does not provide their full history; they simply mark old administrative divisions as historic (with an H). For example, in *Geonames.org* some Roman provinces such as Germania Superior are marked as a historical first-order administrative division - ADM1H. A solution for this would be beneficial for the entire archaeological digital world, and would make it easier to build bridges between the different archaeological subdomains. In our view this problem is similar to the challenge posed by periods, and systems addressing this issue similar to the Web service iDAI.chronontology (iDAI.chronontology, n.d.) could be a solution.

Systems We Worked With

We started to explore and test existing rule engines. This included JESS (JESS, n.d.) and Drools (Drools, n.d.). Both are Java-based rule engines, but since the licence for Drools is more open and it has a more flexible connection interface, the decision was taken to concentrate on Drools. For experienced Java programmers it is easy to handle. It is possible to con-

Experiments and Results

Tools / Language	rapidrep	Drools	SWRL (with Protégé and Pellet) Semantic Web Rule Language (W3C Member Submission)
Type	proprietary software	open source	Language
Data Model	self defined, relational	self defined, relational	incorporated into an ontology
Skills needed	Java, SQL, Excel	Java, SQL, Hibernate	RDF/OWL
Time to first prototype	- (needs internal Model and ETL)	-- (needs internal model, ETL and setup of the system)	++
Performance	++	++	- Protégé is not built to handle huge amounts of data
Remarks/Experience	Nice overview of results (in Excel) easy to understand	Needs IT-experts to set it up Very flexible and powerful	Needs understanding of Open World Assumption

Figure 2. Our experiences with the tools we tested.

nect to and load data from various sources, including the possibility of connecting to RDF-data via Apache Jena. However, the link to RDF-data needs to be set up manually, and the data is then transformed into an internal data model, which means that it is necessary to define one model and to map and dump the different sources into it, as with the normal Data Warehouse approach. This requires extra effort and can lead to errors within the mapping.

In addition, we worked with RapidRep (RapidRep, n.d.), a commercial tool. One of its strengths is that for non-programmers it provides many functionalities via a front end, so helping close the gap between domain experts and programmers. Rules are defined in Excel sheets that are understandable for both groups. However, here also it is necessary to set up an internal relational model, and RapidRep does not support RDF semantics natively.

Both Drools and RapidRep worked and performed very well. But as LOD, RDF and the representation for coins based on *Nomisma.org* has become more widely used in the community, we concentrated on solutions that include the semantics that are already given and supported. Reasoners like Pellet (Sirin et al., 2007) understand natively properties like *owl:sameAs*, etc. With SWRL (Horrocks et al., 2004a) we found an approach where the rules can still be expressed at a high level. Unfortunately, SWRL is only a W3C member submission, and not a recommendation, and it is therefore only supported by a few reasoners, including Pellet. We also did a number of tests within Protégé (Protégé, n.d.) where Pellet can be included as a plug-in reasoner.

An example of a rule would be one stating that the authority of a coin needs to be active at least until the end of the period of production of a coin type. In SWLR it would be encoded as:

```
nmo:hasEndDate(?X, ?D) ∧ nmo:hasAuthority(?X, ?A) ∧ nmo:hasEndDate(?A, ?T)
∧ swrlb:greaterThan(?D, ?T) → hasError(?X, R4)
```

Translation: If an object X has the property *nmo:hasEndDate* with the value D, and X has a connection to the object A via the property *nmo:hasAuthority* and the value T, and if D is greater than T, we have an error. The reasoner in this case adds (infers) an additional statement into the data, the property *hasError* (from the local namespace) to the object X with the value R4.

When working with reasoners, it is important to understand their underlying concept. With the Pellet reasoner that is part of the OWL world, the Open World Assumption (OWA) was our basis. This means additional information might exist, but that the reasoner only takes things for granted that are explicitly pointed out. When writing our first rules it took some time until this lesson was learned. When comparing objects and trying to check if two objects are different by using OWLs *differentFrom(?x-,?y)*, the results were not always what was expected. In order to take into account the OWA, we had to explicitly include into the model that, for example, Nero and Augustus are different persons. Just having two different URIs does not mean that they are different, since it is possible that someone could add *owl:sameAs(?x,?y)* for them. Thus, the open world assumption could be explained as: Anything that is not stated explicitly could be true, while the closed world assumption would be the opposite approach. Sequeda (2012) provides more details on this.

In order to query the resulting error messages with SPARQL in Protégé, it is useful to store the model with the inferred statements. This can be done in Protégé within the File menu under “Export

ID	Rule	Name	No of cases	Reference Query	Reference Size	Ratio	Query Type	Query
6,7	1	Portrait	205	coins_type	4261	0,048	Inconsistent	w3.org/2003/01/g
6,7	2	Start Date and End Date fitting	405	coins_type	4261	0,09505	Inconsistent	/3.org/2003/01/ge
5	3	Start Date after End Date	5	coins AND types	11717	0,000	Inconsistent	w3.org/2003/01/g
6,7	4	Denomination	45	coins_type	4261	0,011	Inconsistent	3.org/2003/01/ge
6,7	5	Mint	1	coins_type	4261	0,000	Inconsistent	.w3.org/2003/01/
6,7	6	Material	54	coins_type	4261	0,013	Inconsistent	w3.org/2003/01/g
4	7	Diameter	20	coins	8272	0,002	Inconsistent	.org/2003/01/gec
/	8	Diameter Weight existing	1196	coins	8272	0,14458	Missing	rg/2003/01/geo/\
/	9	Start - End Date - missing	32	coins_type	4261	0,008	Missing	/.w3.org/2003/01,
/	10	Tests Diameter Weight	413	coins	8272	0,050	Missing	org/2003/01/geo/
8	11	Diameter Weight	13	coins	8272	0,002	Outlier	org/2003/01/geo,

ID	Rule	Name	No of cases	Reference Query	Reference Size	Ratio	Query Type	Query
6,7	1	Portrait	181	coins_type	5209	0,035	Inconsistent	w3.org/2003/01/g
6,7	2	Start Date and End Date fitting	103	coins_type	5209	0,020	Inconsistent	/3.org/2003/01/ge
5	3	Start Date after End Date	0	coins AND types	12719	0,000	Inconsistent	w3.org/2003/01/g
6,7	4	Denomination	28	coins_type	5209	0,005	Inconsistent	3.org/2003/01/ge
6,7	5	Mint	0	coins_type	5209	0,000	Inconsistent	.w3.org/2003/01/
6,7	6	Material	2	coins_type	5209	0,000	Inconsistent	w3.org/2003/01/g
4	7	Diameter	9	coins	9155	0,001	Inconsistent	.org/2003/01/gec
/	8	Diameter Weight existing	2116	coins	9155	0,23113	Missing	rg/2003/01/geo/\
/	9	Start - End Date - missing	9	coins_type	5209	0,002	Missing	/.w3.org/2003/01,
/	10	Tests Diameter Weight	0	coins	9155	0,000	Missing	org/2003/01/geo/
8	11	Diameter Weight	13	coins	9155	0,001	Outlier	org/2003/01/geo,

Figure 3. Overview and metrics of two different executions on CNT data. The second run (bottom) was executed about one month after the first; as can be seen, the reference sizes had also increased in this time. The ID column on the left refers to the IDs of Table 1.

inferred axioms as ontology …". For small amounts of data this worked very well. However, with increasing data volume more memory must soon be provided to Protégé by increasing the heap size. This can be done by changing the Java call parameter -Xmx while starting Protégé (under Windows this can be done in the relevant run.bat file, for example: –Xmx 4G sets the heap size to 4 gigabytes). However, it is important to note that Protégé is designed as an editor, and not as a database. With realistic data sizes, performance troubles are encountered even with increased memory, and currently we are investigating how to overcome these performance issues; either by using a different tool setup, or by using approaches such as SQWRL (O'Connor and Amar, 2009).

Apart from the rule-based approach, pure SPARQL, OWL, or SPARQL SPIN can also be used, as is explained by the World Wide Web Consortium (W3C, n.d.). However, the built-in functions of SWRL, such as *swrlb:greaterThan*, turned out to be very useful, resulting in shorter and more readable rules. An overview of existing functions can be found under section eight of Horrocks et al. (2004b). Figure 2 summaries our experiences to date.

Results in Application to Other Datasets

During our experiments on the rule systems, we used the results to improve the AFE data and to correct inconsistencies. We then chose another dataset for application of the rules in order to a) see how useful the rule system is, and b) demonstrate that it can be applied to other datasets without major adjustments. In order to do so, we selected data from the project *Corpus Nummorum Thracorum* (CNT, n.d.). The CNT database contains a virtual meta-collection of ancient coins of Thrace, a region that covers parts of modern Bulgaria, Northern Greece and European Turkey, and consists of data about Thracian coins located in museums and private collections from all over the world. The goal of CNT is to generate a typology of Thracian coins.

One of the challenges was that there might be exceptions to our rules or the domain experts might want to add comments for later usage or explanation, but that at the same time different persons were working on the system. In order to handle this, and to come up with a method that can be employed independently of the actual system in use, a prototype solution based on Excel files was implemented, with a separate spreadsheet for each main rule. Each execution of the defined rules at a given point in time results in an Excel file. The different domain experts can then work on separate copies of the file and add comments to the different cases. The next time the rules are executed, the spreadsheets are read once more and comments on cases that still exist are transferred to the new spreadsheet. This turned out to be very practical method, avoiding the need to check things repeatedly. In addition, some metadata, for example the first time a case was discovered, can be carried over.

The Excel file also contains an overview with a small metric. Currently, this shows eleven different rules (some of the main rules include sub-rules). These are categorized into rules addressing inconsistencies, missing data, and the highlighting of outliers. Depending on the rule, the reference size as shown in Figure 3 differs, containing either the number of coins linked to a type (*coins_type*), all coins (*coins*), or the sum of all coins and defined coin types (*coins AND types*). The Ratio is calculated by dividing the *No of cases* by the *Reference Size*.

CNT deals with Greek coinage so that rules 1-3 in Table 1 were not included. The reason for this was that many issuers are not yet integrated into *Nomisma.org* and the accordingly their chronological data still needs to be established by the domain experts. Furthermore, inferring the material of coins based on the denomination is less reliable for Greek coins than it is for later periods.

The other rules in Table 1 were included. The resulting mappings are presented in Figure 3 below. The Query column on the right contains the full SPARQL query used to generate the results on the Nomisma.org RDF dump.

Summary and Conclusion

One goal of LOD is to link existing systems. Within the field of numismatics this process is still in progress, and currently the individual systems are responsible for their own data quality. This can be ensured to some extent by good modelling of the data using the features of the underlying system. Data entry on the front-end is also a good place for defining rules, and so avoiding errors being included in the data in the first place (both should be employed, and not just one). For example, a number of Roman emperors struck coins for other members of the imperial family, or for predecessors to whom they wished to proclaim a particular relationship. Therefore, within the front-end of AFE, the usual order found in other databases of entering the data on the issuer and the person portrayed was reversed so that the person portrayed is entered first: a list of possible issuers then appears, thus avoiding incorrect combinations of issuer and portrayed. There might be additional ways of entering data, e.g. by imports. The bottom line is that data quality needs to be addressed at different levels and should be applied as soon as possible. What is more, this can also make things more comfortable for people working with the system.

Previously, since the modelling and front-end were different for each system, it was simply not possible to exchange or reuse data between them. Thanks to *Nomisma.org*, it is now possible to use the same modelling (at least for the 33 institutions that use it already), and therefore rules defined on this level can be shared and evolved in a collaborative way. Our goal here is to set up and publish a prototype version of rules that can be reused by others without adoption efforts. The community can test and improve them in order to also handle special cases. The result would be an improvement of the rules for all, and an increase in quality within the open data. Once the rules are accepted by the community, they can also serve as the basis for a quality metric. This is not per se new, and has already been mandated, for example by Hyvönen et al. (2014).

Several errors were found within the AFE data that could be corrected. The same was true in the case of CNT, and we are sure there are still errors to be found. The moral of the story is to beware of trusting the data of others without applying (your own) rules: as you will see once you have carried out this exercise.

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When All Agents Die: Analyzing the "Failures" in an Agent-Based Model of Human Foraging

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Abstract

When running a simulated social-historic scenario, we often find situations in which all agents die, even though the simulated population appears to grow in the first steps. Is this a signal that something is wrong in the computer model or its implementation? We analyze this issue in our computer model of cooperation and cultural diversity among hunter-gatherers in prehistory. We have calculated more than 11,000 possible parameter combinations, taking into account the growth and decay of the population and the availability of resources in the environment. When the initial population is too scarce or too big for the local availability of resources, it begins to decrease until it disappears. This can be a very trivial test for the Malthus condition, but we have discovered that there are other important correlations affecting social and economic factors that should be explored.

Keywords: agent-based models, hunter-gatherers, parameters test, social simulation

Introduction

In this paper, we discuss how models may be used to make inferences about the most remote past, when humans depended for subsistence on hunting and gathering. Our hypothesis begins as an extremely abstract model and adds degrees of behavioral sophistication, which influence the results. These influences are discussed in a step-wise fashion so that the reader can see how changes to the model's assumption influence outcomes.

Although the models being used in this paper are agent-based computer simulations, we describe the interaction of variables in the models using equations. To understand how this is translated into an agent-based model, the reader is referred to commented code published recently at the CoMSES Network-OpenABM

https://www.comses.net/codebases/f16c9d1c-8c90-42dd-9ef4-d2f5980ac8a8/releases/1.0.0/

Testing Different Scenarios

First Scenario: Simplest Foraging Behavior

We have implemented a series of computer models in which "virtual" hunter-gatherers survive on what they randomly find around them, with no technology for resource acquisition, with a catchment area constrained only by technical limitations in transport and mobility, and without any mechanism of social interaction allowing for cooperation: there is no transfer of food, technology or labor force. This scenario is typical for foraging behavior, where it is assumed agents should find, capture and consume food containing the most calories while expending the least amount of time possible in so doing (Del Castillo and Barceló 2012; Smith 1983; Stephen and Krebs 1986; Winterhalder and Smith 1981). If such an assumption were true, we would say that hunter-gatherer's survival would depend just on the availability of resources, and the nature of economic behavior would be merely adaptive. We take this simplified hypothesis, to explore some of their behavioral consequences.

In our virtual world, agents are not individuals but reproductive units (two adults and a number of descendants). The amount of labor available for hunting and gathering is based on the number of members the reproductive unit has; the agent survival threshold adjusts to the number and age of its members. The algorithm can be run with alternative survival threshold values but we offer here results for an assumed fixed average value of 2,000 calories per individual day (Cordain et al. 2000; Eaton, Eaton III, & Konner 1997; Hill et al. 1984; Leonard 2014; Pontzer 2015; O'Dea 2016; O'Keefe et al. 2010; Simmen et al. 2017; Ströhle et al. 2010; WHO 1991). One-time step (cycle or "tick") in the simulation roughly represents what and where an agent is able to do and move in six months, therefore at the agent level the threshold value is defined as 730 kilocalories multiplied by the number of labor units in this household.

Each time an agent ("family") cannot obtain energy up to the summed survival threshold of the entire family, it loses one of its members (labor unit), and the survival threshold and labor capacity is redefined for the remaining members of the household. In the same way, every 30 ticks (what roughly equals the average time a child needs to arrive to reproductive maturity), a new agent is born, and will live until the total acquired energy is below the survival threshold. There is additionally a stochastic mortality mechanism (death by accident or illness). When survival is possible and the number of members in an agent (expressed in labor units) is greater than a variable parameter, the current agent reproduces and gives birth to a new agent, who has with half the parent labor, the same technology, and the same identity. Our model clearly distinguishes from the more complex demographic engines to generate agents in hunter-gatherer scenarios (Olives et al. 2015; Olives et al. 2018; Smaldino et al. 2013; White 2014; White 2016). The purpose of this exercise is to discover the global dynamics of the simulated agent population, in terms of an increasing or a decreasing trend, and not to reproduce an existing ethnographically described population.

In the simulation, the environment is divided into equally sized patches. Agents move within an area defined by a variable radius, fixed at startup, and whose variations are explored building alternative scenarios. This radius depends on the transport technology available at each moment. Each patch of the virtual environment has a number of RESOURCES (r_i), measured in kilocalories (kcal). The availability and abundance of resources are assumed to vary normally through the landscape; therefore, we have used a Gaussian distribution of values. By modifying the mean, we explore different scenarios (a poor versus a rich world). The standard deviation of resources in the world has been fixed for all the simulations. The year cycle has two differentiated seasons, so that in the cold-dry season, the availability of resources is half of the availability of resources during the warm-humid season. Resources at each patch have also a DIFFICULTY level (h_i). It is also a normally distributed parameter counting the difficultness of resource acquisition.

Social agents survive only if they have success in acquiring energy available in the environment by means of hunting and gathering. It is modeled in terms of a simple energy transfer from the environment to the agent up to the limit defined by the survival threshold (Garfinkel et al. 2010; Iwamura et al. 2014; Young and Bettinger 1992). In our case, the energy each agent acquires is:

$$E_i = R_j f_{i(t)} - Surv_i$$

Equation 1

The agent takes from the environment what it can extract according to the amount of labor it has. This appears as the factor ($f_{i(t)}$) in the equation, the acquired proportion that the agent has effectively obtained by means of its labor and technology, which is multiplied to the amount of resources existing in the actual patch (R_j) in kilocalories. Given that we assume in the simplest scenario there is no storing capacity, what the agent takes from the environment is just what it needs at current time - the survival threshold ($Surv_i$).

A specificity of our model is that agents do not just extract resources from the environment, but there is also an additional factor of difficulty affecting the probability of survival (Equation 1). The transfer of energy from the patch to the agent is mediated by the difficulty of access, and how labor+technology

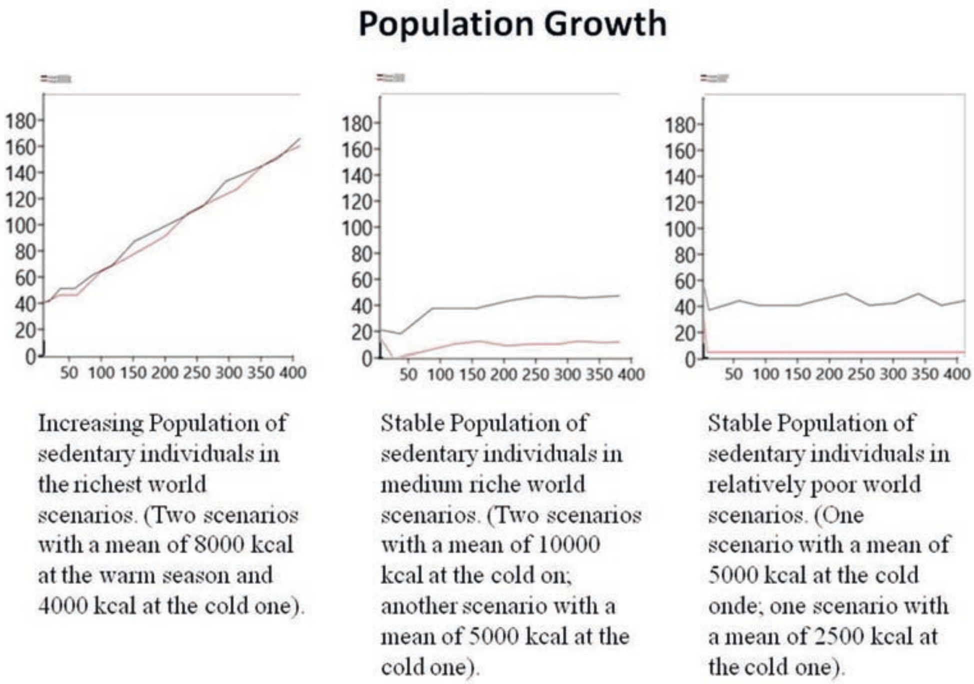

Figure 1. Results of the first scenario foraging behavior and with an in increasing resource irregularity fixed for a standard deviation = 1000 kcal.

allows acquiring a percentage of energy. The proportion of the total resources at the patch extracted by the agent is then:

$$f_{i(t)} = \frac{1}{1 + \frac{1}{hi(t) \times li(t)^{\beta i(t)}}}$$

Equation 2

In other words, agents get the quantity of kilocalories they need from the patch they are situated, provided they have enough labor to compensate for the difficulty of resource acquisition. As already defined in case of Equation 1, fi(t) measures the proportion of existing resources at the actual location the agent can obtain. It depends on the quantity of labor available at this time step (li (t)), the efficiency of the technology at hand (βi(t)), and the local difficulty (hi(t)) of obtaining the resources existing at that place, harder to obtain in the cold season than in the warm one. The maximum value for fi(t) is 1, indicating the amount of work available and the effectiveness that current technology (βi) contributes to compensate for the difficulty of accessing resources. When the value of fi(t) is less than 1 but greater than 0, we can deduce that the working capacity and technology available only allow obtaining a proportion of the available resources.

A rich world scenario would be that in which there are plenty of food and resources available, and the reduction of resources during the cold season has no effect on survival. We have modeled different hypothetical "rich world scenarios," on the assumption that the mean of resources in the environment at the worst season exceeds many times the survival threshold of virtual families. In our model resources diminish at odd cycles ("cold" season) and they recover the initial value at even cycles ("warm" season).

We have implemented the model in such a way that at odd cycles, when resources do not regenerate naturally, the amount of resources available in each cell should be equal to the half of what existed at the warm season minus what the agent extracted at the previous time-step. Therefore, a gathered patch will still be worse than an unharvested patch even after the shift to the cold season. At the next cycle, resources on each cell are re-initialized to the value they had at the last warm season. Obviously, in rich enough worlds, seasonality does not have any impact, but when the mean of resources in the cold season is below survival threshold, survival is at risk.

Initial, exploratory work suggests that "rich" environments appear when resources during the warm season are above 13 times the survival threshold.

It is not a surprise that in these conditions, most

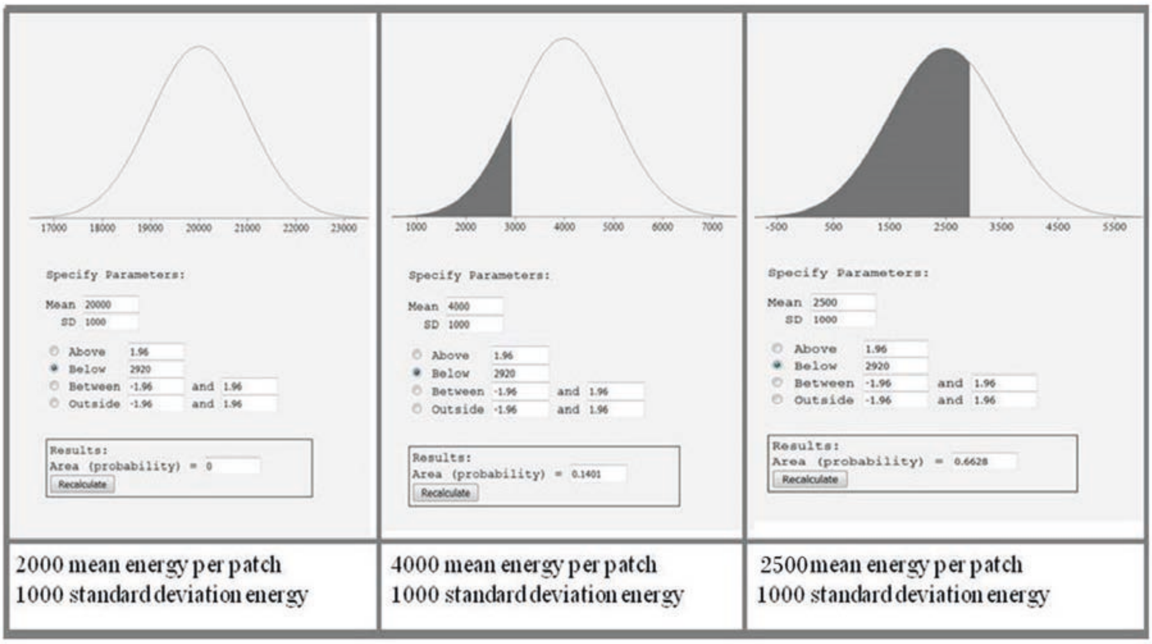

Figure 2. The results show the probabilities of finding enough resources for survival in three different scenarios of resource availability for an example with 4 labor units.

agents live and population grows if there is enough food for everyone (Figure 1). Even in the case of sedentary agents (radius of movement fixed to 0), a population will survive or even increase, provided there are resources well ahead of the survival thresholds. This is the classic Malthus hypothesis. Our results are consistent with modern work on Malthusian growth computer simulations (Lanz et al. 2017; Peretto and Valente 2015).

Given that the amount of resources has been simulated in terms of a Gaussian variable with a fixed standard deviation, and agents have been initialized on random patches at start-up, it becomes easy to calculate the probability of finding enough resources for survival using normal probabilities. In the rich scenario with a mean of 20,000 kcal of energy in the environment at the warm season (and a uniform irregularity estimated in terms of a sd = 1000), there will be 0 probability to find some area with a quantity of resources below the survival threshold. In "poorer scenarios", the probability of being on a patch where survival is not possible will be higher (Figure 2). The prior probability of survival can be computed from the probability of availability of enough resources (Barceló et al. 2014). In the case of mobile agents, such prior probability changes every time the agent takes the decision to move.

Second Scenario: Mobility Decisions

We have introduced a mobility mechanism to increase the probability of survival when an agent does not find enough resources locally: move-to-another-place. This has been implemented as a mobility decision (Figure 3). Two options are open for selection:

1. Stay at place
2. Move to another place

At first, the agent evaluates its chances of surviving in the next season. The expected quantity of resources at next cycle is calculated by the agent on the basis of its knowledge of the current season and the nature of the next season, and on the amount of energy it has already taken from environment at the present cycle. Consequently, if

$$\textit{Expected}\ R_{i\,(t+1)} - e_{i\,(t)} > \textit{Expected}\ \text{survival-threshold}_{(t+1)}$$

Equation 3

on the next time-step, the agent remains at the patch and does not move. Otherwise, it moves randomly to any other unoccupied patch in a fixed neighbor-

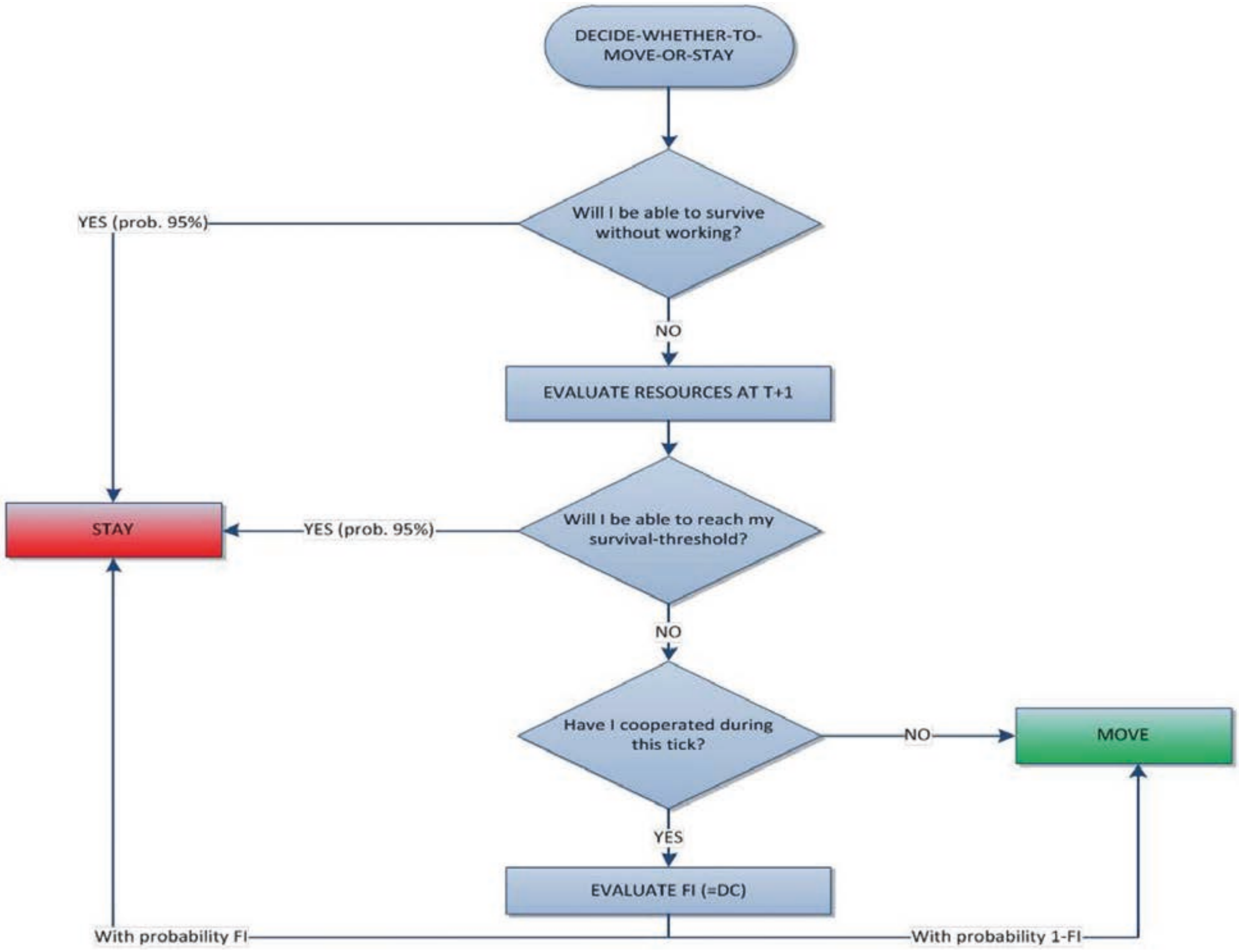

Figure 3. Functional diagram of the model showing agents decisions process.

hood, limited by available technology for transport and movement. This dynamic is very loosely based on the marginal value considerations from classical optimal foraging theory (Gurven et al. 2006; Keeley 1988; Keene 1979; Konner and Eaton 2010), although in a very simplified way.

Obviously, prehistoric hunter-gatherers nor hunter-gatherer bands known in historical times hardly ever displaced randomly and hunted-gathered at any place within a constrained neighborhood (Grove 2009; Perreault and Brantingham 2011). Displacement among hunter-gatherers can take many different and varied forms:

- the displacement of all the population or a part of it,
- wandering randomly through the lowest cost-surface until finding the richest place, or the place where enough resources are most accessible, or
- going directly using the most direct and fastest way to the place where there is a memory of plenty of resources.

Because the condition is to move to an empty patch, there is not any chance that two agents coincide at the same patch. In any case, we have added a small amount of random noise (a randomly selected 0.05 % of agents always move). We have considered that a small amount of system stochasticity is necessary to avoid the risk of local minima. Exhaustive testing of simulations with and without such amount of random noise suggests the advantages of this approach.

If the next season is a warm one, even the proportion of resources the agent has extracted in the previous season will be naturally reproduced, and

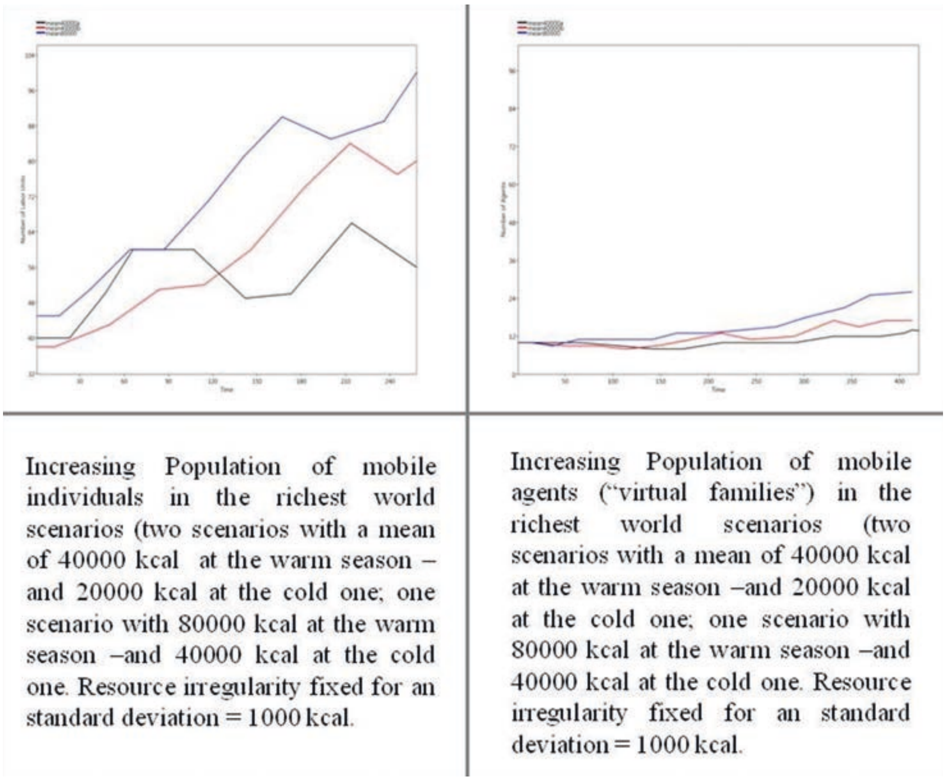

Figure 4. Survival comparative charts explains how introducing mobility in a rich world (when the availability of resources in the cold season exceeds seven times the survival threshold), does not affect survival, and hence population grows.

survival will be possible. In case the next time step is a cold season, local resources will reduce drastically, and moving to another place will be imperative.

Exploratory work on different scenarios suggests that when the availability of resources in the cold season exceeds seven times the survival threshold, introducing mobility does not affect survival. Consequently, population grows, both at the level of the number family members and the number of families in the territory, although the growth of families increases at a much slower scale (Figure 4).

The reason for the differences in the rate of growth lies in the social nature of reproduction. Within a family, the number of members increases geometrically linearly related to the availability of resources, whereas within a landscape, the number of families increase arithmetically depending on the internal growth of family members. The simulation reproduction engine generates a new family when the previous family's labor units grow to greater than or equal to a specified size threshold of 10. Other values are possible, and their effect on hunter-gatherer survival should be explored (Lesthaeghe 1998; Rijpma and Carmichael 2016; Skinner 1997). We think that this threshold for family "leave and cleave" is fixed in most societies through social norms. In this paper, and to reduce the parametric space, we have fixed it for the examples in this paper, using average family sizes from ethnological work in Patagonia (Barceló et al. 2015a). We have just added 5 % of random noise to account for accidental variability.

To our surprise, when introducing small amounts of random mobility (up to a 2 % of the landscape) in most cases, even in relatively rich worlds, all agents die, when in the sedentary scenario survival was guaranteed (Figure 5). The rate of decreasing population is logically related with the mean of resources, and it is independent of the radius of mobility.

Starvation and population extinction only happen when the prior probability of survival in the cold season is below 55 %, based on the number of patches where resources are above the survival threshold for a virtual family of 4 members in average. However, it is relevant that even at higher, prior probabilities; population diminishes, when in the same circumstances, sedentary populations grow. In any case, the key factor is still the availability, irregularity, and accessibility of resources. The amount of mobility has no impact on the rate of mortality. We have simulated scenarios where agents are allowed to move in the immediate 2 % of the total environment looking for enough resources, in the immediate 12.5 %, 50%, and even at the entire territory. In the absence of any

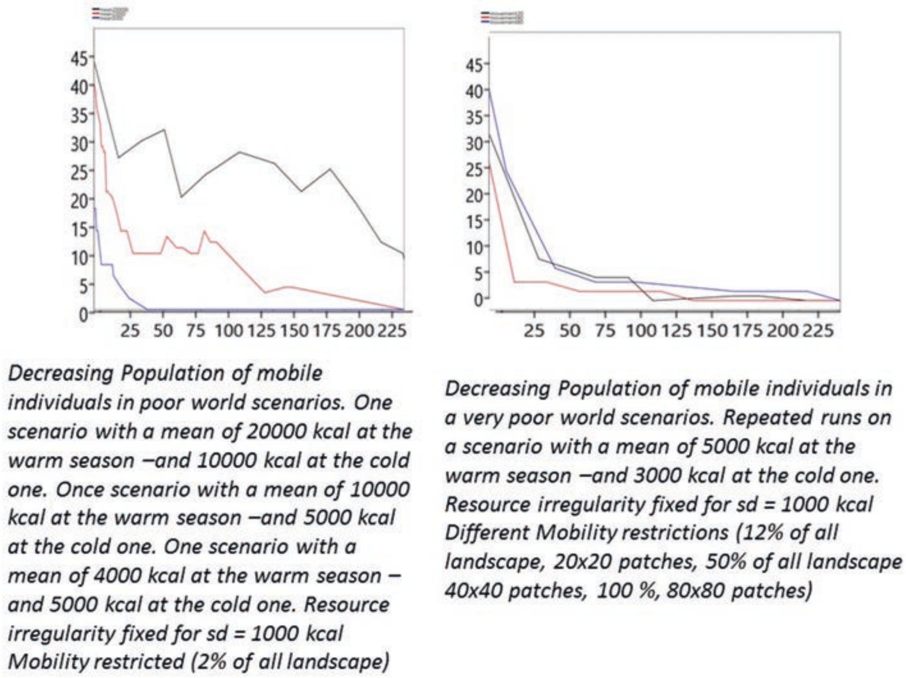

Figure 5. Comparative charts showing the variation in the conditions of survival introducing small amounts of mobility.

other factor, mobility in itself cannot increase the probability of survival.

In our results we see that when resources diminish, families decrease their number of members, and hence the amount of labor available to compensate for the local difficulty of accessing existing resources. If the simulation started with families of four members (where the number of members is a Poisson distributed parameter with small values of lambda, that is, with very small variability), the mean number of labor units per family rapidly converges to two. In such conditions, although the survival threshold also diminishes, the probability of acquiring enough resources is affected by the local difficulty.

Mobility increases stochasticity in all simulated scenarios. That is, at each run of the same scenario (with the same values and the same parameters at start-up), the evolution of the population differs. This is a consequence of the increasing irregularity in agents' revenues. The mean energy acquired by labor unit is fairly constant in all simulated scenarios, but when adding mobility, its standard deviation also increases, varying enormously from one cycle to the next. That means that although most agents behave in the same way trying to extract the maximum amount of energy they can find locally; the local availability varies. We have fixed such an irregularity assuming a Gaussian distribution with a standard distribution of 1000 kcal. This value should be interpreted as a very small irregularity in the richest world (12.5 % of variation) and increasing irregularity as the mean of resources is lower, arriving to 40 % of variation in the poorest scenario).

Third Scenario: Introducing Technology

The use of technology for increasing revenues is the main characteristic of human beings for at least the last 3.3 million years. We have studied the probable effects of technology –see parameter β in equation 2- in medium rich worlds (where the amount of resources in the environment at the worst season exceeds two times what a family of 4 members needs for survival). We explore technology effect as an exponent rather than a multiplied factor because of its implicit non-linearity compared with the influence of the labor force (Hekkert et al. 2007; Kremer 1993; Ruttan 1996; Solé et al. 2013).

In medium rich scenarios, the effects of technology on population growth of sedentary agents are small but relevant (Figure 6). Much more evident are its effects on mobile populations. If survival is at risk when opting for mobility even in a medium rich scenario, technology multiplies the effects of labor on the accessibility of resources and the probabilities for survival, and it reverts population decrease.

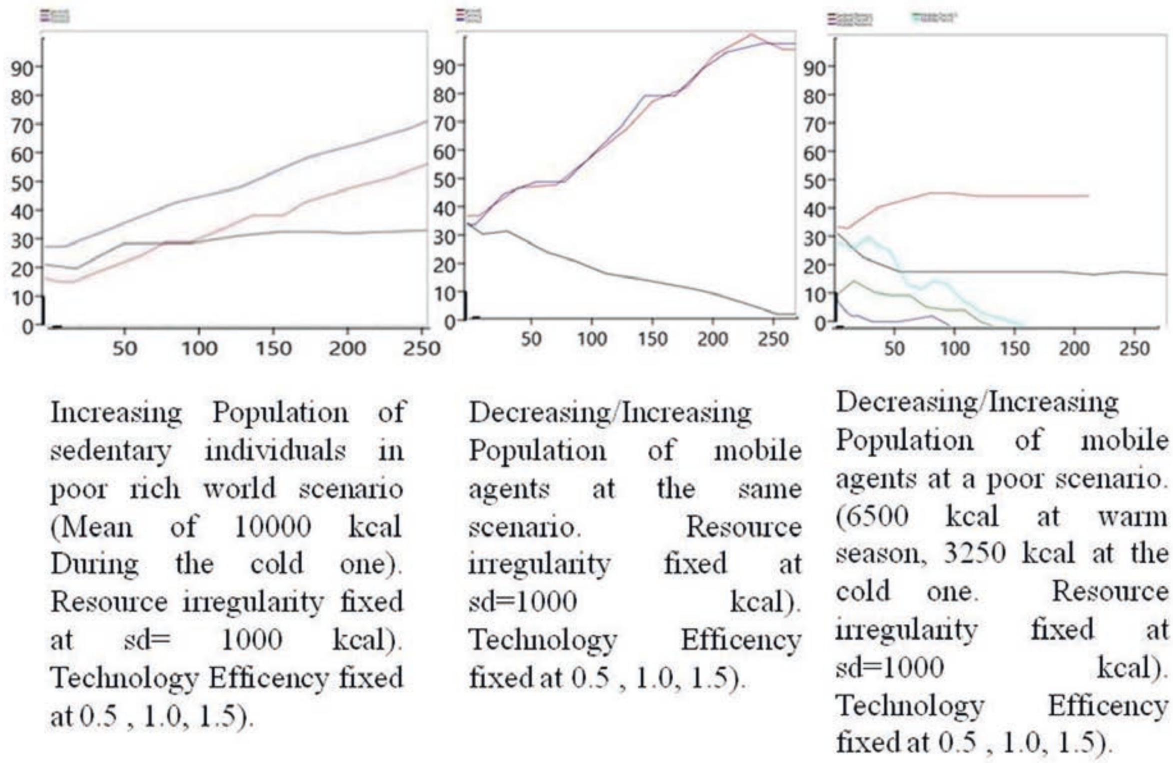

Figure 6. The advantages of technology related with three different scenarios of sedentary/mobile/resources abundance.

At poorer environmental conditions, technology by itself cannot revert the effects of mobility, stochastically increasing movements to low value cells, and as a result, most agents die in relatively short periods of time.

Fourth Scenario: The Effects of Cooperation ("Collective Hunting")

In our model, cooperation in a hunting-gathering band does not imply the transfer of subsistence, because what an agent acquires is limited to its current needs. Consequently, there is no surplus of food to be transferred, but there is always a surplus of labor not used when resources are rich enough and easily accessible with the current labor capability. This surplus of labor can be used in an abstract form of "collective hunting" (Hill 2002; Packer and Ruttan 1988). In our case, higher values of difficulty (h_i) are compensated by adding labor units from different agents in adjacent patches. In so doing, we understand "collective hunting" in the way it has been used in robotic simulation: each agent makes its own decisions based on its ambient circumstance, and the cooperation may emerge through local interactions among the robots, which is beneficial to the task (Cao et al. 2006).

In the simulation, agent i receives cooperation in form of labor (additional labor units) from agents that have labor in excess for their own survival, only in the case it is unable to reach its individual survival threshold on its own, and there is an agent with an excess of energy in the vicinity. If the amount of energy and the level of productivity is enough, the agent will act individually and collect as much energy as it needs.

There is no compensation for the excess of labor exchanged or calculation of differential costs. That is to say, there is no obligation to "return the favor." There is a constraint in the quantity of labor a "rich" agent can transmit to an agent "in need". Each agent has a "FREE-LABOR" attribute expressing the number of labor units the agent can lend to another without compromising its own survival.

The number of labor units a family needs to reach her survival threshold is:

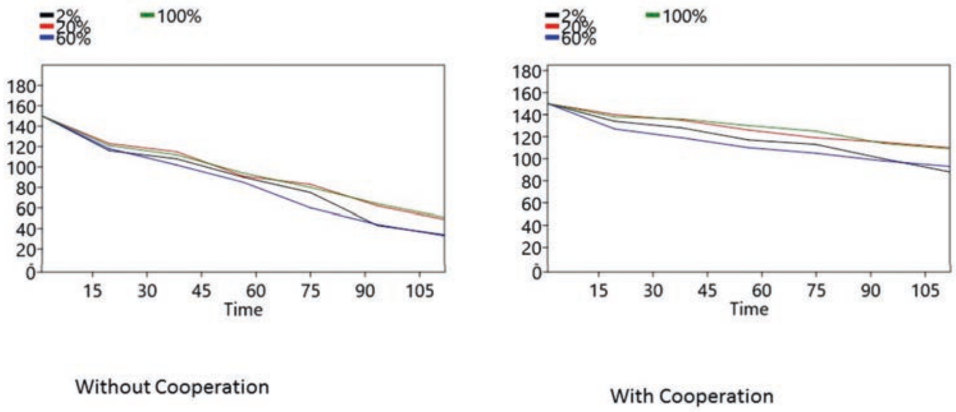

Figure 7. Decreasing population of mobile non-cooperative/cooperative individuals in a poor world scenario (one scenario with a mean of 6500 kcal at the warm season and 3250 kcal at the cold one. Resource irregularity fixed for and standard deviation = 1000 kcal.

$$Surv_i = \left[\frac{\bar{e}_i}{h_{i(r_i - \bar{e}_i)}}\right]^{1/\beta_i} - l_i$$

Equation 4

where $\bar{e}_i$ and $\bar{e}_l$ represents the acquired energy at the current tick (see Equation 1), l_i the actual quantity of labor, β_i the actual technology to compensate for the local difficulty (h_i) of obtaining the resources existing at that place, and r_i the amount of resources existing in the actual patch. The first term is the additional number of labor units the family needs to reach its survival threshold; and the second term, l_i, is the actual number of labor units the family has. This equation is the result of clearing $Surv_i$ in Equation 1 and adding relationships expressed in Equation 2 to calculate $\bar{e}_i$.

If the first term is greater than the second term, it means that the family does not have enough labor units to reach her survival threshold. Therefore, the value of $Surv_i$ (Equation 4) will be greater than zero (and thus FREE-LABOR = 0). In those cases where both terms are equal, the number of necessary labor units will coincide with the number of labor units the family has. Consequently, the value of ST will be zero (and FREE-LABOR = 0). However, if the second term is greater than the first term, it means that this family has plenty of labor units to reach its survival threshold (and thus ST = 0). The result of the subtraction will be negative (the family has extra labor units). The value of this subtraction (with changed sign) is precisely the amount of free-labor the family will lend another family in need.

With this supplementary labor, the system calculates the aggregated productivity [$\Delta f_{i(t)}$] of an agent member of a group $G_{i(t)}$:

$$\Delta f_i\ (t) = \frac{1}{1 + \frac{1}{\left[h_i\,(t).\ (\sum j \in G_i(t) l_j\ (t)^{\delta\beta j(t)})^{\theta_i\,(t)}\right]}}$$

Equation 5

where $G_i(t)$ is the total amount of labor the group of agents that cooperate with agent i and $\delta\beta_i(t)$ the maximum technology within the group. There is an additional parameter modifying the total effect of aggregated labor at the social aggregate[1] ($\theta_i(t)$), capturing the idea that cooperation is less needed when there are plenty of resources. Productivity after cooperation is assumed to depend on labor productivity $p_i(t)$ in such a way that the higher the productivity the lower the expected returns of cooperation. Given a parameter

$$0 < x_i < 1$$

$$\theta_i\,(t) = 2 - (x_i)^{\alpha}$$

Equation 6

where α is a free parameter, so that 0 <= α <= 2. Therefore, θ_i is between 2 (when that particular patch

1 We expect that social cooperation will be less likely with distance. Instead of including a separated parameter for distance, we restrict calculations to the neighborhood group, which is defined as a list of agents within the neighborhood radius with similar "culture." Details of the "cultural" algorithm cannot be given here. The reader is referred to Barceló et al. 2014, 2015a.

is very poor in resources, $x_i = 0$), and 1 (when that particular patch is very rich in resources, $x_i = 1$). In general, we have calculated

$$xi = \frac{r_i}{mean\_resources\_on\_patches + (3 \times standard\_deviation\_resources\_on\_patches)}$$

Equation 7

Such an assumption produces a probability around 0.001 that x_i be greater than 1. In any case, if the result of the above equation is below 0 or above 1, x_i is reset to 0 and 1 respectively.

Preliminary results show that when fixing free parameters at medium/low values (Population = 150, Average technology = 1.05, Diversity = 0.1, labor average = 5, average storing factor = 0, internal change = 0.01) in a typical "poor resources" scenarios (mean resources on warm season patch = 6500 kcal), the advantages of cooperation are clear. Probabilities for survival increase in 53 % on average, although cooperation by itself is no guaranty of survival (Figure 7).

In any case, the size of the area where hunter-gatherers look for possible cooperants has no relevant effect on the advantages of cooperation. This result is unexpected. Cooperation apparently should depend on the distance over which social interaction can be defined. According to our preliminary results, the amount of cooperation is not inversely proportional to the distance between agents, defined in terms of the size of area where cooperants can be found. In our simulations, we have not measured any significant impact of interaction radius, given that the decrease of population is fairly similar when interaction is limited to the 2 % of the total area, when maximum allowed distance is fairly large (the agent can explore 60 % or even 100 % of the environment to look for prospective cooperants). In any case, this result cannot be used to deny the fact that ask-for-help diminishes with distance. The scenario we have explored here has a low population density (150 agents occupy just 5 % of available space). If population declines because of the poor resource scenario, there is less opportunity for helpers as well and so the population cannot recover. This fact creates isolated groupings of families that cooperate only amongst each other.

This result also shows the increasing stochasticity of human survival in conditions where cooperation is necessary. Cooperation may contribute to survival, but if agents rely on help from neighbors to make decisions, the final result is affected by uncertainty. Only when the technology for movement – transportation – allows an agent to contact with any neighbor in any place, then there is a clear increase in the chances of survival. However, when there are barriers to cooperation, either by physical distance or social distance (cultural identity), the advantages of cooperation are hardly evident.

Conclusions and Further Work

In this paper we have explored the old Malthusian view on population decreasing exponentially when resources are below a survival threshold. In our model, survival is not only affected by the raw quantity of existing resources, but by the "difficulty" of acquiring what is needed to survive. That means the more mobile the resource and the more difficult its spatial accessibility, the higher the difficulty, and therefore the more labor is needed to obtain resources up to the survival threshold, and more time is needed for the task. When more labor is needed, survival is less probable because the survival threshold increases given the higher quantity of people to be fed. In this scenario, any mechanism to increase the efficiency of labor has relevant effects.

When resources are low, not only because of their scarcity but because they are hard to obtain, hunter-gatherer survival is at risk because the amount of labor available to compensate for the local difficulty of accessing existing resources diminishes. When introducing small amounts of random mobility (up to 2 % of the landscape) in most cases, even in relatively rich worlds, all agents die, when in the sedentary scenario the chances of survival were higher. Our simulations show that random mobility is only a partial solution to compensate for the high difficulty and relatively low volume of resources at place.

In this paper we have just explored the consequences of random mobility. It is no adaptive decision, and it implies no rationality nor optimality criteria. Obviously, we need to implement a different mechanism that may include the selection of a better cell, using the calculation of prior probabilities for survival, and also considering the possibility of "memory." This would allow the agent to move towards the cell the agent remembers was a "good" one if it is not "far away" from the actual position. In any case, it is interesting to observe that even in the case of random movement agents do not bounce along until they settle on a good patch where they survive and grow. This is a consequence of seasonal variation in resources and the impossibility to survive at the current site in the cold season, once a majority of resources has already been harvested, and the remaining energy is well below survival threshold. An efficient technology for storing energy would be needed.

We have considered the effects of technology and social cooperation on survival in the simplest imaginable scenario. We have fixed low values of technology just to test the effects of social cooperation in the worst circumstances imaginable. We have tested the effects of collective hunting on survival in a scenario of very poor resources, where a population of agents has low chances of survival. If cooperation is not particularly beneficial in the case of rich scenarios, where resources are easily accessible, collective hunting does increase the chances of surviving in the case of low-density, decreasing populations.

Our results show that the advantages of cooperation are clear (probabilities for survival increase in 53 % of the scenarios on average), although cooperation by itself is no guaranty of survival. We have also shown that the radius of mobility, determined by the level of transportation technology, does not affect the advantages of cooperation. Increased chances for survival are as high in the case of using horses to travel through the entire landscape on a single cycle, as in the case of travelling on foot over a restricted 2 % of the area. In general, our results match those by Dyble et al. (2016), insisting on cooperation and sharing as concentrated within small clusters of households. These clusters represent one part of a multilevel social structure, and allow access to important cooperative relationships.

The effects of collective hunting as a form of cooperation have been studied by Skyrms (2004) and subsequent work (Antonioni, Tomassini & Buesser 2014; Gold 2012; Perc 2011; Pereira and Santos 2012; Skyrms 2008; Tomasello et al. 2012), and our results coincide with what would be expected according to this theoretical framework. Other important work that takes into account the effects of cooperation in the success of hunting is Janssen and Hill (2014 and 2016). All these works show the relevance of going beyond traditional views of prehistoric hunter-gatherers in terms of animal foraging behavior maximizing their net energy intake per unit time. Following Mithen (1988), we can say that while optimal foraging theory has been of considerable value for understanding hunter-gatherer subsistence patterns, there is a need for a complementary approach to human foraging behavior which focuses on decision-making processes and social cooperation.

Hunting in the past seems to have been a much more complex activity than expected, whose success, and hence the posterior probabilities of survival, are less deterministically affected by the availability of animals in the area or the efficiency of available technology. We need to incorporate social dynamics well beyond the standard animal foraging model: animals rarely cooperate, but cooperation is what made us humans. If a social agent cooperates with another agent, the chances of hunting success are higher, even in the case of low animal availability, or the difficulty in capturing them with available technology. Here, there is a social decision ("to hunt together or to hunt individually") that form the basis of Skyrms (2004) suggestion. According to this approach, we have modeled a cooperation mechanism in which an agent will cooperate with another:

1. when someone in the appropriate neighborhood will ask for help given its inability to survive using its own means. This neighborhood is constrained by the technology for mobility (MOVEMENT is a global parameter);

2. there is enough cultural similarity among both agents (the survival threshold needed to define the possibility of labor exchange is defined according the local circumstances);

3. the helping agent has labor in excess, and it can only contribute with what it does not need for its own survival;

4. only one agent can be helped at each time. The procedure is implemented so that all possible FREE-LABOR is given to the first agent asking for help. The remaining FREE-LABOR is invested in surplus (additional energy) when the current value of the STORING FACTOR is set > than 0.

Our results show that when following these constraints, cooperation increases the chances of survival, but in poor scenarios cannot avoid the outcome of the entire population starving.

We are conscious that connections to archaeology are only left implicit in this paper. For the moment, our aim has been to create a theoretical model of the possibilities of survival in prehistory, when technology was poorly efficient, and it hardly contributed to survival. There is a theoretical impossibility in obtaining empirical data to test the expectations that prehistoric people had about the advantages of mobility, the effects of available technology and the risk minimizing factor that comes from the possibility of increasing labor force cooperating with neighboring groups. We have intended to have some formal validation; that is, a test that the hypothesis may be true *within an artificial* (although objective) formal system (Barceló and Del Castillo 2016, Fforde 2017; Hasan and Tahar 2015; Yanow and Schwartz-Shea 2015), providing a reference background against which we can explain variability. The past cannot be reconstructed from archaeological data alone, because a given dataset contains insufficient regularities for predictive theorizing. Our computer model is just a hypothesis about *the more probable* behavior given some well-defined, prior assumptions, and it adopts the form of a deductive statement, whose foundation is merely formal. The model has been parameterized using ethnographic analogies and results of previous archaeological experiments (Barceló et al. 2015b). In any case, the model can be easily enhanced by introducing some archaeological corollaries of agent behavior, like the production of garbage as a sub-product of hunting and gathering, the material remains of residential places or burials signaling the number of deaths. A quantification of those elements would allow a partial empirical testing of the hypothetical model (Conte and Paolucci 2014; Geller 2014; Lee et al. 2015; Windrum, Fagiolo & Moneta 2007).

In the social sciences, models are often presented uncritically as faithful representations of reality. In this paper, we make no such claim. We argue instead that our models of hunter-gatherer survival are useful as devices for interrogating some prior hypotheses about human behavior in Paleolithic times. Does it mean that the model is wrong? Not necessarily (Epstein 2008). We have not yet explored alternative and more complex scenarios, because we were interested in simulating the simplest scenario to evaluate the effects of social cooperation and the transfer of labor force in the worst imaginable conditions. In any case, even this most simplified and abstract model suggests the enormous variation of effects a single decision or strategy had, and it contributes to understand the basis of randomness in human action, especially at times where social organization was dependent on local resources and the local configuration of those resources.

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The Dynamics of Brazilian Rock Art Landscape: An Agent-Based Modelling Approach to Theories

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Abstract

The first attempts at synthetizing the diversity of Brazilian rock art sites and the spread of graphic similarities envolved a certain amount of environmental determinism and traditionalism. We propose an agent-based model able to verify the possible effects of theoretical perspectives on the landscape. Our model uses a number of hunters moving randomly and a set of shelters where they can make new paintings according to simples rules. Three different mechanisms can be modified: exogenous (by nature, some shelters are fit for painting and not others), endogenous (by culture, some shelters are preferred by each hunter, and not others) and cumulative (shelters with paintings are more attractive). Compared to the archaeological context, only exogenous and cumulative constraints seem able to result in a landscape where a few shelters are concentrating most of the paintings. Endogenous constraints alone seem unable to produce the same results without another mechanism for transmission.

Keywords: agent-based modelling, archaeology, rock art, Brazil

Introduction

When studying the relations between rock art and the landscape, it is not uncommon for archaeologists to have a kind of static approach. Geographic features, such as drainage systems and elevation changes, are looked at and compared with the site location. Present-day vegetation and, if possible, paleoenvironments are studied as a whole. Despite the fact that very few sites are the result of a single occupation, we tend to forget that none of these prehistoric artists saw exactly what his or her predecessors – and followers – could actually see. Some authors even argue that each occupation was able to abstract and mentally delete all previous work. And yet, they chose the very same spot.

In this article, we propose an analysis of different theoretical approaches used in Brazilian rock art studies through agent-based modeling, in order to identify possible variables in the process of landscape formation (Cegielski and Rogers 2016). While our concerns and hypotheses are grounded in Brazilian archaeology, it could easily be translated and adapted to other contexts around the world. The next sections have been adapted and formatted according to the ODD protocol (Grimm et al. 2010).

The Model

Purpose

Brazilian archaeology has a long tradition of environmental determinism. It has roots in Julian Steward's cultural ecology theory and was imported by Betty Meggers and Clifford Evans during the 1960s, at the time of a large project sponsored by the Smithsonian Institution, called Programa Nacional de Pesquisa Arqueológica (Funari 1999). At the time of these large continental classifications, the easternmost part of South America was labeled "marginal" as semi-arid environmental conditions were deemed

Figure 1. Location of the main archaeological occurrences of the Nordeste Tradition in Brazil.

as unfit for complex cultures (Silverman and Isbell 2008, but see mostly pp. 3-28). Academic interest grew in the late 1970s, when a large series of rock art sites were identified and studied in the northeast region of Brazil. The Serra da Capivara would quickly become a locus of heated discussions and debate as dating started to lean more and more towards a late Pleistocene occupation (see Meltzer, Adovasio, & Dillehay 1994; Pessis, Martin, & Guidon 2015).

Leaving the question of antiquity aside, these new sites quickly indicated to archaeologists a larger than expected human occupation for the Holocene period. Palaeoenvironmental studies also showed that those dry and harsh conditions visible today in these regions appeared around the Middle Holocene – later than the oldest widely accepted occupations at that time these sites were found. Changing perceptions of this landscape became a matter of discussion amongst archaeologists and they adopted the concept of environmental refuge.

Following a definition by Jürgen Haffner in 1969, Brazilian geographer Aziz Ab'Saber (2003) defined refuges as those areas where rainforest reaches its maximum retraction under negative conditions (see Prance 1982). In the Northeast region, many refuges are associated with highlands, such as brejos (altitude swamps) and serras (mountain ranges). Archaeological sites in these areas, particularly visible ones like painted rock-shelters, were linked to these cycles of growth and retraction (Ab'Saber 2003).

Refuge theory was seen as a deterministic, yet semi-dynamic, framework to understand long-term occupation in the Northeast. The Serra da Capivara, as well as areas in the Seridó and the Chapada Diamantina, have since then been interpreted in the same terms for the whole Holocene period, when climate gradually shifted from wetter to drier conditions (Araújo et al. 2005).

Archaeologists formulated a second approach of cultural transmission: the concept of tradition. First coined in the 1960s to acknowledge recurrences of style and themes, archaeologists then expanded and used it as a classification scheme. Behind the repetition of similar paintings, a tradition means that artists transmitted a specific knowledge from one generation to another, during long periods of time and in significantly large areas (Prous 2005). Today, occurrences of the Nordeste tradition are broadly dated between 10,000 years BP and 6,000 years BP, in a region covering more than 500,000 km² (Martin and Vidal 2014).

Just like the refuge theory, a system based on this concept of tradition implies the existence of an initial configuration at some point in the past, from which there would be very few changes, like moving to a neighboring valley or adding a few details to the main graphic corpus. Unfortunately, there has been very little discussion on the real content of such traditions. They have been used in Brazil as a general explanation, without any further detail on their effective mechanisms.

We propose considering these two determinisms as exogenous (nature-based) and endogenous (culture-based). Both mean that the choice of new paintings in a new location is given by a set of rules that has been predefined, be it externally or internally. Does this difference have an influence over the landscape? Can it be used to help us better define the concept of tradition? What are the alternatives?

Our main purpose, then, is to study clustering. This phenomenon is occurring at multiple scales in Brazilian rock art studies:

1. A figure has to be identified individually, as to where the painting starts and stops;

2. A panel is broadly defined by blank spaces between groups of figures;

3. A site is a collection of panels on a particular outcrop or shelter;

4. An area covers a series of sites in an environmental or geological context.

The first three conditions listed above are common to most rock art studies around the world. The fourth condition of analysis, while also occurring in other parts of the world, is expected to reveal a particular combination in each new case.

In northeastern Brazil, this last type of clustering is particularly interesting when considering sites showing figurative art. Two large clusters have been studied in the last decades: the Serra da Capivara and the Chapada Diamantina. Despite their similarities in terms of style and complexity, there is a 300 km gap between the two. Between these areas there are completely different categories of paintings, mostly non-figurative. If we assume archaeological surveying has been properly undertaken, there must then have been a very precise choice or strategy as to where and how to place rock art, at a regional scale.

Entities, State Variables, and Scales

The model was written with NetLogo 6.0.1 (Wilensky 1999). It is based on two sets of agents.

- One agent is rock-shelters, used as non-moving agents with two attributes: the number of paintings, and a value symbolizing their quality. Here, quality is defined as a very general and undefined variable that would broadly include stone properties or ritual aspects. It would be whatever reason one could have to be attracted by it.

- The other agents are hunters, who could represent a single person or a whole ethnic group. They move randomly on the territory and have no attributes. Their activity is unique: painting.

- Furthermore, the world they evolve in is composed of patches, which have specific coordinates and a variable used in the process of calculating the hunter's cognitive map, as detailed below.

The whole territory has not been defined in terms of a precise scale. In general terms, it could represent a few km² or a whole region. We expect that two neighboring patches are sufficiently distant that they have no or few influences on one another.

Process Overview and Scheduling

The basic principles of the model are quite simple. Randomly reaching a rock-shelter, a hunter uses the quality variable to decide if it is possible, or convenient, to add a new figure. The attribute is a threshold against which a random number test is made. If the test fails, that is, if the random number is superior to the threshold, the hunter will just continue to move until it reaches another shelter. If it succeeds, a new painting is added to the rock-shelter, and the hunter continues to move on. The models stop when the first rock-shelter reaches a hundred paintings.

On every tick, each hunter has the opportunity to make one move and, eventually, one painting, on a turn-based logic. Time has not been defined in terms of scale. Just like the size of the patches, it could represent a day or a year. We expect both these scales to be set in accordance (i.e., a day for a small area, a year for a larger one).

Design Concepts

The main question at this point is the definition of the main variable called "quality." To avoid unending discussions as to how exactly people were deciding to draw paintings or not, the content was deliberately kept undefined – it just could be anything. It represents the fact that, at some point, for some reason, a decision was made on a certain basis. How exactly this basis was determined, externally or internally, is what draws our attention.

Coding such a variable when it is defined externally is relatively straightforward. In this perspective, a unique environmental configuration is given. It is common to all the hunters. Rock-shelters are sandstone or limestone, high or low, exposed to rain or not, etc. No human action could ever change such a configuration. At the start of every run, the program just gives the attribute a random number between 0 and 10. Low values mean poor conditions, while high values indicate particularly good conditions.

Indeed, such environmental variables seem to have been, at some extent, a real motivation for site location in the northeast region of Brazil. In the region of the Chapada Diamantina, in the state of Bahia, there is a clear difference of style, pigmentation and motives between the neighboring calcareous and sandstone regions. In Morro do Chapéu, many large sandstone outcrops bear figurative and collective scenes while, in the limestone basin of Irecê, which is also drier, there is a particularly high concentration of geometric designs. Natural properties thus played an important part in the choice of places (Etchevarne 2007).

Defining the same variable internally is more complicated. From this point of view, each hunter needs an individual definition of what is an adequate place to make a painting. Again, there wouldn't be any precise content, and such a definition could range from the shape of a boulder matching a mythological figure to the location along trade routes.

The cognitive map was generated with a matrix of the size of the world, here composed of 33 by 33 cells. Each patch of the matrix is filled with a random number, corresponding to the value given by a particular individual for this spot. As every hunter gets his own matrix at startup, the shelters end up with a number of quality variables equal to the number of hunters. Their value ranges from 0 to 10, depending on the random number of the patch in which they were created. Again, a low value means that, for an individual hunter, a shelter is not a proper place to make a painting. Importantly, in this case, two hunters can have very different ideas of what is proper and what is not.

In order to choose between one perspective and the other, each variable was also associated with a slider going from 0.0 to 1.0, called mod.amb and mod.cult. In order to analyze how external definitions affect the landscape, we have to zero the cognitive map slider; on the other hand, we have to zero the environmental definition to consider an internally defined notion of place.

Initialization

At time 0, a user-defined number of shelters and hunters are randomly spawned, all with their own variables already set. Those values will be used according to the relative importance the user wants to give them with the modifier sliders. Each run of the model will then generate a different scenario, even when the configuration remains the same.

Analysis

We ran the model a number of times with each configuration, and the results were analyzed with a few metrics. First, we gathered statistical data on each final distribution: the sum of all paintings, the mean number, variance and standard deviation. We displayed a sorted distribution for each shelter, from the most to the least painted, as well as the ratio between paintings and ticks. Second, we added more precise information about the dynamics of the landscape

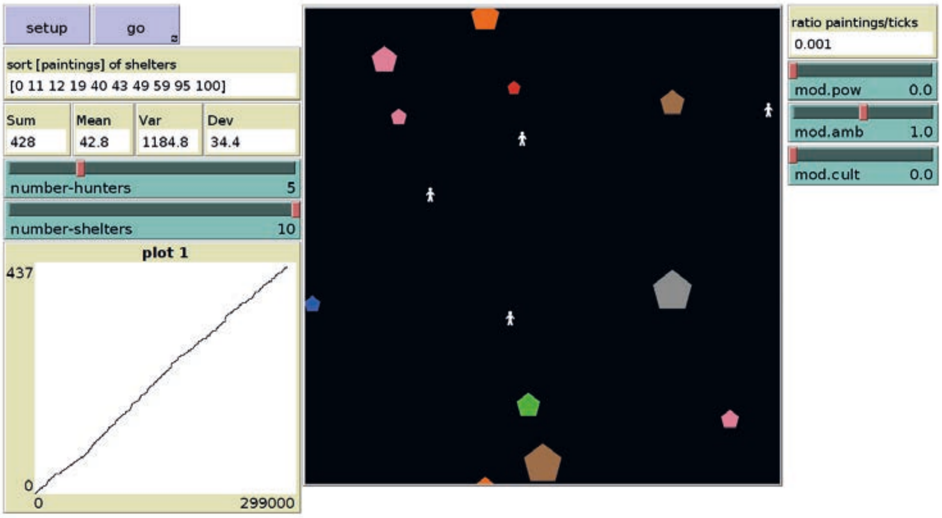

Figure 2. A typical context generated under the exogenous approach, with three large shelters and a few smaller. Two sites have no figure at all.

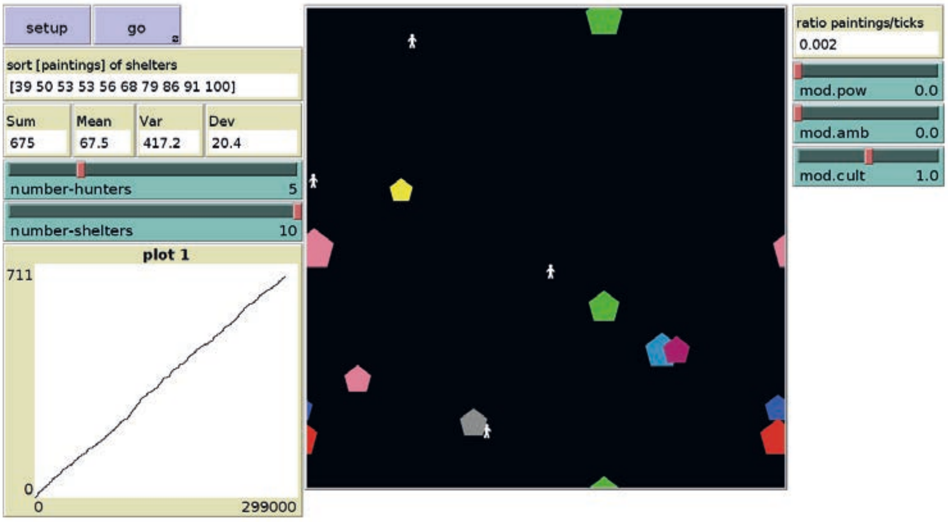

Figure 3. A typical context generated with endogenous configuration, resulting in a fully populated landscape.

construction, with a plot giving the evolution of time against the sum of all paintings.

We first looked at the environmental scenario, where a single threshold value is given externally for each shelter. As expected, those sites with the highest threshold received significantly more paintings than those with a low value. For a series of 10 runs, based on 10 shelters and 5 hunters, we found a mean sum of 552 paintings per run, with a variance of 1064.2 and a sigma, or standard deviation, of 32.6. These results confirm the high differences between the shelters: some are densely painted and others are not.

This scenario points to a high clustering, which is particularly interesting for us, as it matches a phenomenon we observe in real archaeological context: some outcrops are fully painted while the neighbouring ones may be completely empty. The dynamic plot, nonetheless, shows a regular, linear evolution, meaning the same number of paintings has been regularly added across time.

The second scenario was based on a cultural approach. Here, every hunter gives its own individual value for each shelter, resulting in a complex array of thresholds. Because of their variability, all of these different cognitive maps have the effect of scattering the results, giving them a near-random appearance. In effect, for the same series of 10 runs with 10 shelters and 5 hunters, we had a mean sum of 812 paintings by run, a variance of 69.3 and a sigma of 8.3. Most shelters ended with a high number of paintings, blurring the variability among them.

In these terms, a cultural scenario shows very poor results for the archaeologist. Even considering the most densely painted areas, like the Serra da Capivara National Park, where more than a thousand sites have been identified so far, their general spatial distribution is more selective than these results show.

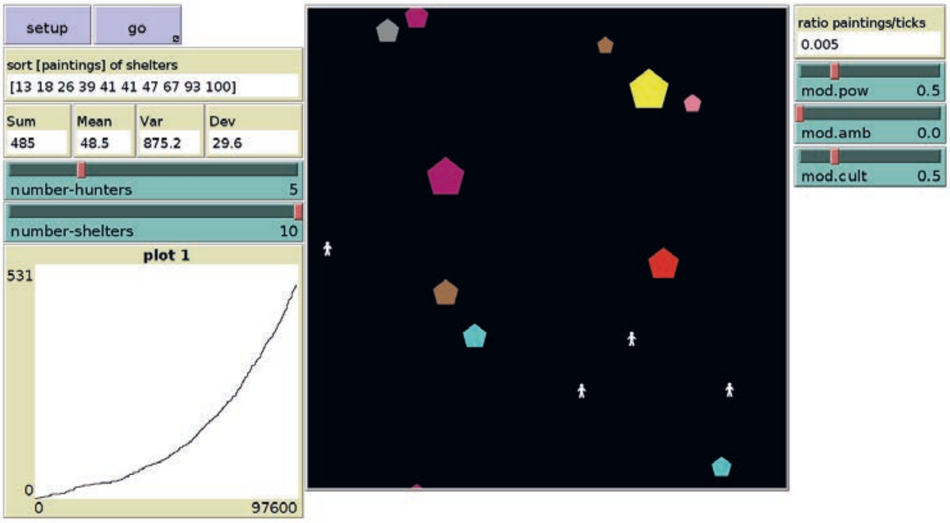

Figure 4. An example of clustering generated when the cumulative effect is relatively high (0.5). Here, half the shelters show a limited number of figures.

If we consider the kind of final landscape our model creates, we should expect it to match one an archaeologist could study in the field. In this case, an environmental perspective seems best fitting because it is able to produce clustering. Shelters receiving a higher value are always preferred to those with low threshold values. An endogenous definition of places, on the other hand, is tied to each hunter and results in a scattered, near-random distribution of rock art. These results are not very satisfactory, because they do not match the archaeological data collected to date.

Resuming the whole process of creating paintings in rock-shelters to a limited set of variables is, of course, a shortcoming. The utility of such a model lies in its ability to test our hypotheses and, eventually, to indicate flaws. In this case, we have reduced a complex reality to two agents: rocks and hunters. The result of their interaction – paintings – is our primary interest and yet, it has been treated as a by-product, completely irrelevant to the whole process. The number of paintings appears only in our statistics, and it has no influence over the movement or the threshold.

Sub-Model: A New Mechanism For Transmission

In the introduction, we presented this dual approach between nature and culture as a theoretical choice, possibly unconsciously made, by many researchers. In the model, the idea of a cultural transmission is reduced to the fact that each hunter, who might also represent an ethnic group, has been using a single static cognitive map through time. Their contact with empty sites or previously painted shelters was of no importance. Such lack of a real mechanism for transmission may explain our unsatisfactory results.

If we ca not assume archaeologically that different hunters or ethnic groups were in direct contact, the only way to establish some kind of interaction would be indirectly, through the paintings. As we have seen, the site formation is a dynamic process, growing and unfolding as more and more people used the same location to paint their graphics. That is, as we understand it, a cumulative effect. It means that the number of paintings in each rock-shelter cannot remain a hidden variable, used only for statistics.

To insert this hypothesis into the model, we added a string defining that a certain value would be incremented to the threshold based on the number of existing paintings in a shelter at the moment of each new test. Thus, even a place disregarded for painting by most hunters could end up with a significant number of graphics if a single agent was able to make a head-start. Hunters disliking a specific spot could also be motivated to make new figures if the shelter is already well decorated.

Running this configuration requires using the mod.cult or mod.amb sliders. Indeed, a cumulative effect alone is not able to create any landscape at all, as it needs, at the very least, one first painting. As our aim is to examine its role on an endogenous definition of the threshold, our tests are made with a balance of the two sliders, mod.cult and mod.pow, each at 0.5. The average values are shown on a table, always considering 10 shelters and 5 hunters, based on 10 runs each.

Sum	Var	Sigma	mod. pow	mod. cult
767.8	261.4	16	0.1	0.9
635.6	480.2	21.8	0.2	0.8
607.4	492.8	21.2	0.3	0.7
642.2	535.9	23.1	0.4	0.6
455.2	671.8	25.8	0.5	0.5
469.6	698.6	26.3	0.6	0.4
375.4	830.7	28.6	0.7	0.3
431.2	849.9	29.1	0.8	0.2
383	1099.2	32.9	0.9	0.1

Table 1. Average cumulative effect applied to endogenous rules results in clustering as the weight of each new painting grows.

We can then assess the variation with a pure endogenous scenario. The changes are visible even with a low cumulative effect: there is a significant drop in the total number of figures, and the statistics show higher variance and standard deviation, indicating that the distribution is more concentrated. The scattering effect of having different hunters giving different values to each shelter seems to be balanced by the attraction of the painted locations. Most runs now show some clustering.

Furthermore, this cumulative effect is also able to change the shape of the landscape construction, plotted as a relation between the total number of paintings by ticks. The plot is not linear anymore, as it becomes easier to make new figures on those shelters where a number of paintings has already been drawn.

Discussion

The whole model reduces a complex situation to simple agents moved by basic rules in order to illustrate how a rock art landscape may have been generated. At first, our tests confirmed that a configuration based on nature, external to human decision, was the only one able to reproduce a clustered landscape where only a few sites are selected to receive paintings. Indeed, when we considered that each hunter or group of hunters defined his own cognitive map internally, the associated landscape showed a near-random distribution. Most shelters were heavily painted as, even when a single hunter didn't value a particular spot, another did. This led us to question the concept of a cultural transmission as "tradition" without explicitly defining any working mechanism.

In order to show how the model could be used to enhance the definition of tradition, we decided to add a variable known as "cumulative effect" that could work as a locus for indirect interaction and transmission between different hunters. In this new context, the paintings left by other agents on a rock-shelter have an effect of the next hunters' behavior. As a result, we showed that a simple cumulative effect was a possible mechanism to explain the construction of a clustered landscape. Yet, this kind of rule doesn't behave like the first exogenous approach: it does not produce clustering on every run. On the contrary, it remains dependent on initial conditions, and shows our real, archaeological rock art landscapes as a matter of probability, or trajectories.

The term tradition has first been defined on a stylistic argument. As the years passed, a new element called emblematic scenes was added to the Nordeste Tradition as precise complex canvases were repeated on distant sites. Yet, few discussions have been made over the mechanisms themselves. Transmission is generally assumed without debating what caused the transmission. It is not our objective to state that preferential attachment was effectively acting in the particular context of northeastern rock art sites. We show that the concept of tradition is not sufficient, in itself, to explain this archaeological spatial distribution.

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Agent-Based Modelling of the Relationships among Kinship, Residence, and Exchange

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Abstract

In the North American Southwest, archaeological research has documented ceramic exchange networks in which spatially proximate households in consumer communities have greatly varying amounts of imported pottery. This paper uses agent-based modelling to gain insight into the processes responsible for these distributions. The agent-based model used here tracks kinship ties among agents representing individuals who give birth, marry, co-reside with spouses, and exchange things in a virtual landscape filled with small settlements of up to a few hundred individuals. Exchange of goods in the model flows through the kinship networks. The results suggest that the differential distribution of goods among spatially proximate households seen in the archaeological cases could result from a small-world network that forms as some individuals move to join spouses in far-off settlements, giving relatives in their home settlement preferential access to exchange goods originating in distant places..

Keywords: agent-based modeling, exchange, kinship networks

Introduction

This paper describes an agent-based model designed to explore some aspects of the relationships among exchange systems, kinship networks, and settlement size. Since the 1970s, archaeologists have modeled exchange systems using either simple quantitative models or computer simulations. The literature on modeling exchange systems is too large to review here, but it is worth mentioning a few early influential examples of archaeological exchange models. These include Renfrew's (1975, 1977) arguments connecting the shape of fall-off curves over distances with highly abstracted "modes" of exchange (such as down-the-line or directional trade); Henry Wright and Melinda Zeder's (1977) computer simulation designed to explore the role of exchange of ritual items in "regulating" the production and exchange of subsistence goods; and Doran and Corcoran's (1985) simulation of production and exchange. Although the latter two examples are agent-based models, the agents are entire villages, and all of these early attempts model exchange at relatively large spatial and/or social scales, without considering the motivations of individuals or households.

A number of recent efforts have built on these earlier attempts by using agent-based modeling to explore various aspects of exchange systems. Among other things, these more recent models explore food sharing among households (Kobti 2012), specialization in resource procurement (Cockburn et al. 2013), the development of market systems (Watts and Ossa 2017), and the importance of small-world networks in distributing obsidian in the Near Eastern Neolithic (Ibañez et al. 2015; Ortega et al. 2014). All the cited models provide useful insights into the operation of prehistoric exchange systems, although none of them address the issues I explore below.

Archaeological and Ethnographic Background

Much of my own archaeological research has involved documenting ceramic exchange networks in the North American Southwest. In these networks, the abundance of imported pottery generally declines with distance from the source zone, but households in consumer communities often have greatly varying amounts of imported pottery despite being located in close proximity to each other (Allison 2000; Allison 2008).

Figure 1, for instance, graphs data from 68 ceramic assemblages that come from Ancestral Pueblo sites in the Moapa Valley of southern Nevada. These sites date between about AD 1050 and 1125 and are scattered along a small stream that creates a linear oasis in the Mohave Desert. Because the sites are small and dispersed, most of these assemblages represent the ceramic discard of single households, although a few assemblages combine materials associated with more than one house. Overall, about 29 percent of the pottery on these sites is one of two types (Moapa Gray Ware or Shivwits Plain) made in the forested uplands north of the Grand Canyon, 75-125 km to the east of the Moapa Valley (Allison 2000; Harry et al. 2013; Lyneis 1992; Sakai 2014). In individual assemblages, however, the percentage of imported pottery ranges from 2 to 69 percent. The wide range of assemblage sizes makes applying formal statistical tests difficult, but Figure 1 shows bands representing 90 percent and 99.9 percent confidence intervals around the mean value across the range of sample sizes represented.

Overall, if the variation among the assemblages was due to sampling error alone, only 10 percent of the assemblages should plot outside the 90 percent confidence band, and (most likely) none would fall outside the 99.9 percent band. Clearly, the variation is not due to sampling error, but appears to reflect large differences in the amount of imported pottery obtained by different households living within short distances of each other.

Similar variation, beyond what could be explained by sampling error, is seen in the relative abundance of San Juan Red Ware on sites in southwestern Colorado dating from the late AD 700s or early 800s (Allison 2008). In that case, red ware pottery was made in a broad production zone located mostly in southeastern Utah, then exchanged eastward into southwestern Colorado. Near the modern town of Dolores, Colorado, about 50 km east of the production zone, ceramic assemblages dating to the late 700s or early 800s include an average of about nine percent San Juan Red Ware, but individual assemblages vary from less than two to more than thirteen percent. In contemporaneous sites twice as far (i.e., about 100 km) from the production zone, near the modern town of Durango, Colorado, the mean percentage of red ware is only about one percent, but individual assemblages vary from zero to more than four percent red ware. Also, neutron activation data shows that people living within walking distance of each other obtained San Juan Red Ware from different parts of the production zone (Allison 2010; Allison and Ferguson 2015).

In both of the cases described, settlements are relatively small. Moapa Gray Ware and Shivwits Plain producers and consumers lived in dispersed communities that included many small, single-household sites and a few larger settlements that housed small numbers of related households. The San Juan Red Ware exchange system involved some villages with populations in the hundreds, but also many smaller settlements that were part of dispersed communities.

Some archaeologists might interpret the variation in the relative abundance of non-local ceramics as reflecting differences in status and access to exchange, but there is little evidence for strong differences in prestige or wealth among the small-scale farmers represented in this case. Instead, I argue that the differential distribution of goods among spatially proximate households probably results from something like a small-world network (as argued by Ortega et al. 2014 and Ibañez et al. 2015), but one that links individuals, not entire settlements, across space.

Ethnographic data suggest that exchange in small-scale societies is strongly structured by kinship relations. Lederman (1986), for instance, describes the trade networks of 43 informants in a highland New Guinea village. On average, each informant had 59 trade partners, 55 of whom were relatives of various kinds. Only about seven percent of the named trade partners were not kin.

Similar quantitative data on trade networks is rare in the ethnographic literature, but it is clear that kinship structures exchange transactions and the movement of goods in many societies. Among the Hopi,

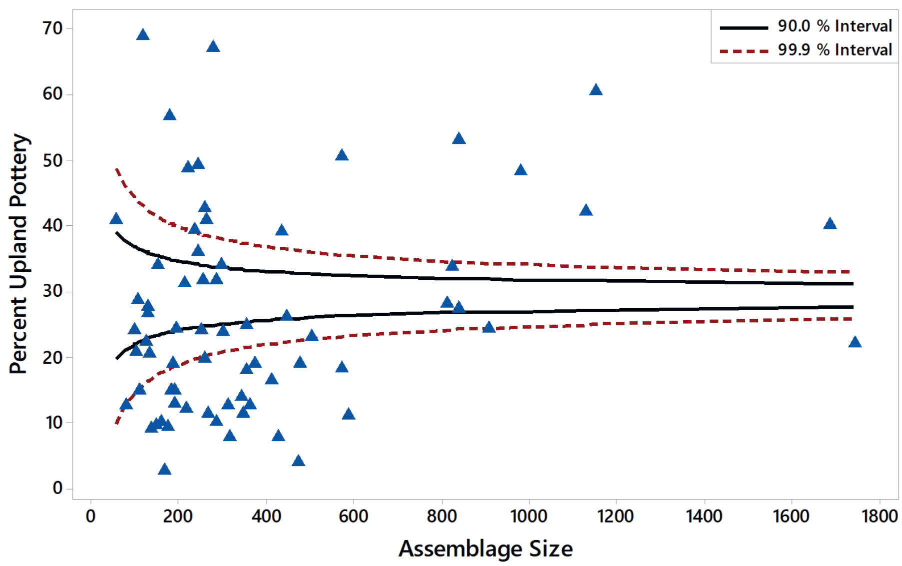

Figure 1. Scatter plot of ceramic data from 68 ceramic assemblages in the Moapa Valley, Nevada. The plot shows assemblage size versus percent of ceramics imported from upland production areas 75-125 km to the east.

a Native American group that probably includes many descendants of the people involved in the archaeological exchange systems described above, the link between kinship and exchange begins soon after birth when "the paternal grandmother and the other paternal female relatives arrive at the mother's house to present their gifts. . . The naming ceremony initiates a whole series of economic ties between the paternal grandmother primarily, and secondarily the other paternal female relatives, and the grandchild, nephew, or niece, as the case may be....throughout life the individual is linked to those who assisted him to enter the world and named him a member of the group by ties that only death can cut..." (Beaglehole 1937:73). At marriage, "… specific personal relations are established by the transfer of gifts and the assumption of new economic obligations on the part of the two principals towards each other and towards the kinship groups to which each belongs" (Beaglehole 1937:75).

Ethnographic data also shows that, while conventions about post-marriage residence vary, people in many small-scale farming societies prefer to marry within their local community, in part because they often have access rights to land from the kin groups of both spouses, and need to live close enough to be able to work the land. But, as Rappaport (1968:102) notes, men cannot always marry locally: "full satisfaction of a preference for local women is unlikely among groups the size of the Tsembaga…Groups of such size are subject to imbalance in the numbers of persons of each sex…" On the other hand, "While unions between men and women of a single local origin confer certain advantages upon both parties and their natal agnatic groups, unions between people of different local origins confer others. Unions across the grain of the land serve to strengthen trading relationships …"

Modelling Goals

The agent-based model described below is an attempt to evaluate several linked hypotheses about the relationship between kinship networks and exchange. First, that the variation seen in the archaeological examples in the abundance of trade ware pottery is due to a small number of people having better long-distance connections across the landscape, giving them easier access to pottery made in distant locations. Second is the idea that these differences can arise simply through variation in kin networks and post-marriage residence, in the absence of pronounced differences in status or wealth. A third idea, though initially more a question than a hypothesis has to do with the effect of increasing settlement size. Do larger settlements lead to larger differences in access to trade goods? Or do larger-sized villages smooth out the demographic variables enough that village endogamy becomes universal and every-body's kin and trade networks are restricted to their home village?

How the Model Works

The model is implemented in NetLogo 6.0, a high-level programming language designed for agent-based modelling (Wilensky 1999; Wilensky and Rand 2015). The model is available for download at <https://github.com/jallison7/kintrade-model>. The choice of NetLogo as a platform involves a trade-off between ease of use and performance. Many procedures commonly used in agent-based modelling are built in to NetLogo as primitive operations, which greatly facilitates coding of the model, and NetLogo's graphical interface makes it easy to visualize some aspects of the model's performance. These positive features also have a downside, however, as they can cause the model to run slowly. As currently configured, the model takes less than a minute to run when the population is small, but the number of operations increases exponentially with population size, and some of the analyses reported below took hours to run. This is probably due in large part to the extensive use of agent filtering statements (when agents search for eligible spouses, for example), which are easy to code in NetLogo but often run slowly (Railsback et al. 2017). Further extensions of the model may require recoding it with attention to improving its processing speed.

The model simulates exchange of ceramic vessels among individuals organized into villages and linked by kinship ties. Specifically, the analyses reported here all use eight simulated villages arranged in a line (although the model code allows the number of villages to vary). This creates a much simpler settlement landscape than exists in the real-life exchange systems, which include a variety of settlement sizes and communities that are more dispersed than the villages created by the model. In NetLogo's graphical interface, the villages are evenly spaced on the x axis and represented as circular areas 30 patches in diameter. Both the spacing of the villages and the representation as circles are display conventions with no affect on the model outcome.

Each run of the model begins with a setup procedure that locates the villages and populates each village with agents representing men and women. A

Run	Females	Males	Total	Sex Ratio (males/females)
1	441	374	815	0,85
2	390	397	787	1,02
3	396	361	757	0,91
4	378	407	785	1,08
5	407	417	824	1,02
6	422	412	834	0,98
7	418	365	783	0,87
8	387	428	815	1,11
9	404	388	792	0,96
10	423	381	804	0,90
Total	4066	3930	7996	0,97

Table 1. Variation in population size and sex ratio after the initial setup procedure in ten test runs with the village-size variable set to 100.

Village	Females	Males	Total	sex Ratio (males/females)
1	63	40	103	0,63
2	57	51	108	0,89
3	44	40	84	0,91
4	67	54	121	0,81
5	47	45	92	0,96
6	50	47	97	0,94
7	66	56	122	0,85
8	47	41	88	0,87
Total	441	374	815	0,85

Table 2. Variation in population size and sex ratio among the eight villages for the first run shown in Table 1.

variable called village-size sets the mean size of each village, although the actual number of individuals created varies randomly, following a Poisson distribution. Each individual created has an equal probability of being male or female. Across a large enough number of iterations of the model, simulated villages are, on average, equal in size to the village-size parameter, and the procedure creates equal numbers of male and female agents. But in any single case, the size and sex ratios of villages vary. As Table 1 shows, in 10 tests of the procedure with the village-size parameter set to 100, the total initial population size for the eight simulated villages varies from 757 to 834, but the average across the 10 tests (799.6) rounds to 800, exactly what it should be. The sex ratio (males/

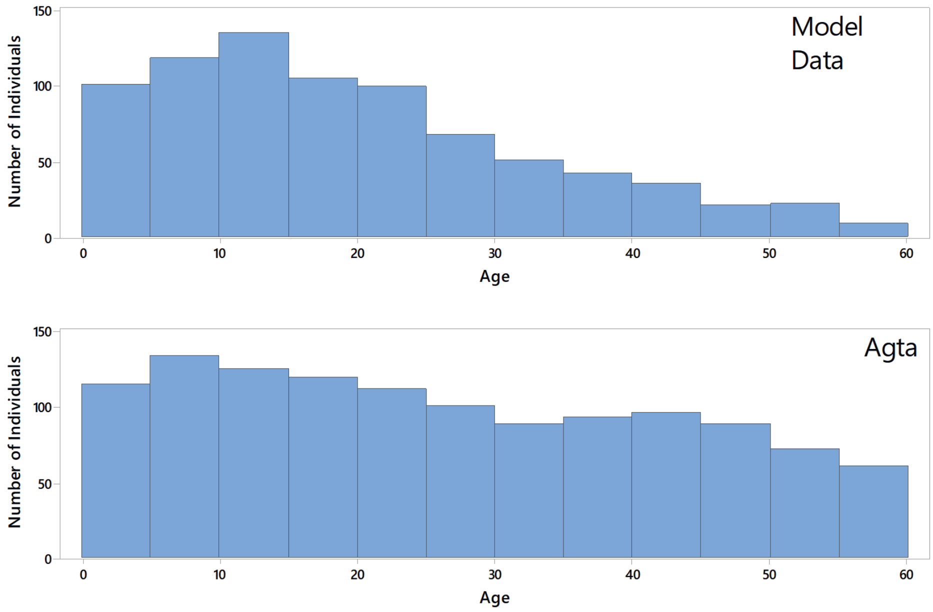

Figure 2. Comparison of the population structure resulting from one run of the model with the observed structure of a modern population from a small-scale society of Agta foragers from the Philippines. The model produces a population that skews younger than the observed population.

females) in the same tests varies from .85 to 1.11, or from about 46 % male to about 53 % male.

Initial population sizes and sex ratios for individual villages vary even more (Table 2). Similar variation in settlement size and sex ratio is common in real-world situations, and it is important to the way the model creates simulated networks of kinship relations.

The individuals created during setup are randomly assigned ages, with every age from 1 to 45 being equally probable. When created the individuals have no kin ties, and the first generation of agents never have parents, siblings, or affinal relatives. They do marry, however. Once all the initial individuals are created, females above the age of 16 search for suitable males to marry. Suitable is defined as over the age of 16, not already married, and within 10 years of the age of the female seeking a spouse. Females first look for suitable spouses within their own village; if none of the males within their village are suitable, they then look for a spouse elsewhere. A variable called max-marriage-radius controls how far from their current village women will go to find a spouse. The model as currently implemented is strictly matrilocal. If a suitable spouse is found in another village, the male moves to the village of his spouse. Because of the variation in population size and sex ratio, and the rules controlling who can marry whom, not every individual is able to marry.

Once the initial generation of individuals has been created, the model begins to run. Each "tick" in NetLogo is conceptually a year, in which all individuals age, some marry, some have children, and some die. In each year of the simulation, unmarried females over the age of sixteen search for suitable spouses as in the initial setup procedure. The birth rate is controlled by a variable called birth-probability, which is the probability that a married female between the ages of sixteen and forty will have a child in any particular year. Children under the age of sixteen never die in the model, so the "birth probability" is better understood as the probability of having a child that will survive to at least age sixteen. A variable called death-probability, representing the probability of death in a given year, controls the death rate for individual agents between the age of 16 and 60. The death rate is constant in the model from age 16 through age 60, but individuals over the age of 60 always die.

Both the birth probability and death probability are variable in the model, although the analyses reported here all use .17 for the birth probability. That means a female who lives to age 40 will have, on average, four children who live to at least age 16. The death probability is also fixed, in these analyses at .05, meaning five percent of individuals over the age of 16 die each year. These values are probably not entirely realistic but were chosen through experimentation that showed simulated populations are approximately stable with those values; in most runs of the model with these settings, the total population decreases slightly, but not enough to threaten the viability of any village. These values create a population structure that seems somewhat reasonable, although it probably skews too young to be realistic.

The top half of Figure 2 shows the age structure of the population after 100 ticks for one run of the model with the initial village size set to 100. In this run of the model, approximately half the population (401 out of a total population of 814) is age 16 or younger, while only nine individuals (about one percent of the population) are 55 or older. The bottom half shows the age structure, up to age 60, for modern populations of Agta foragers who live in the Philippines (Headland et al. 2007). The overall life expectancy of the Agta population is only 23 years, largely due to extremely high infant and child mortality rates. Compared with the population structure produced by the model, the modern Agta population shows fewer children and adolescents (about 35 percent of the population age 16 or under), a much more robust representation of adults between 30 and 55, and more individuals over the age of 55 (five percent between 55 and 60, with additional individuals over the age of 60 not shown in the histogram). Because the model assumes no infant or childhood mortality, compensating with relatively low fertility rates (Agta women average seven births per woman compared to about four in the model), it will probably never precisely replicate the population structure of the Agta or any other comparable group. Still, this comparison suggests the model could be improved through adjustments to the birth and death rates that increase the number of adults surviving after the age of 30. A simple reduction in the death probability would accomplish this, but, without compensating adjustments in the birth probability, it would lead to population increases rather than the approximately stable population achieved with the settings used here.

Each run of the model has a 100-year initialization period, during which several generations of individuals are born, marry, and die. The model tracks a network of kinship relations for each individual through links to their parents, children, siblings, spouses, and first-order affinal relations (i.e., their spouse's parents and siblings). These individual kin networks vary in two important ways. First, because birth, death, marriage, and reproduction all vary randomly, some individuals have larger networks than others. Second, males move when they marry out of their birth village, but remain linked to parents, siblings, and other relatives in their home village. This means that some individuals have relatively expansive kin networks, with links to kin several villages away from where they reside. Other individuals have kin networks that are restricted to their birth village.

After the 100-year initialization period, the model begins to simulate the production and exchange of pottery. Production and exchange continue for 50 years, during which agents continue to be born, marry, and die, and the details of individual kin networks continue to change. Women in Villages 1 and 2, the first two villages at the left side of the NetLogo graphics window, are the potters. A variable called annual-production controls the rate of output of each potter. In each year, individuals ask for pottery from members of their kin networks who live either in the same village or in villages "upstream" in the simulated linear exchange network. This means pots can move around among individuals within a village, or move to the right from villages located further to the left, and therefore closer to where the pottery is produced, but they never move back to the left. Males and females both take part in the exchange, but only adults over the age of sixteen participate. Whether an exchange actually takes place is controlled by a variable called exchange-threshold. If an agent receiving a request to exchange owns more pots than the exchange threshold, then they pass one on to the agent making the request.

Among agents residing in the same village, the order with which the agents seek exchange transactions is random, as is the order with which they select members of their network to ask. But the exchange proceeds one village at a time, beginning with the villages at the left side of the system and moving progressively to the right. Agents continue to request pots until they have exhausted their kin network, or have received a number of pots equal to a variable called annual-demand, which is fixed at five in the analyses reported here.

Results

The analyses reported here are preliminary, representing a first attempt to explore the implications of the model. Even though the model is relatively simple, there are many variables, and it is easy to generate voluminous output. The model allows ten param-

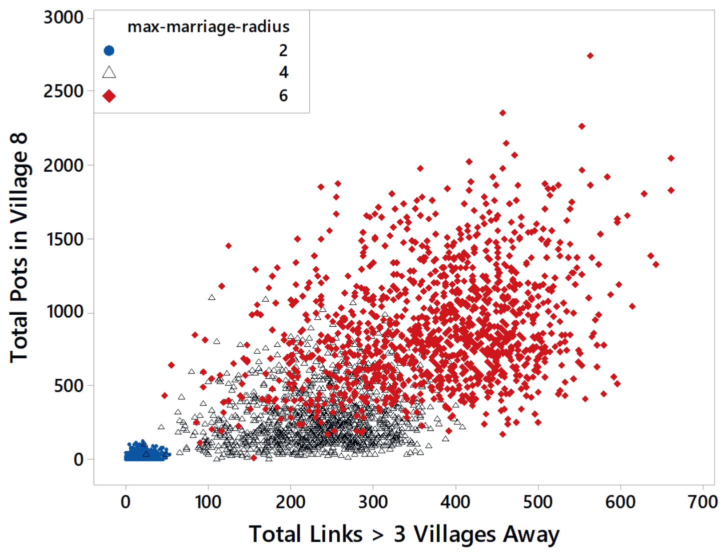

Figure 3. Scatter plot showing the effect of the max-marriage-radius variable on the number of kinship links created to individuals residing at least three villages away and on the number of pots acquired by Village 8 residents in one run of the simulation. These results are from 3,600 runs of the model with the village-size variable set to 500.

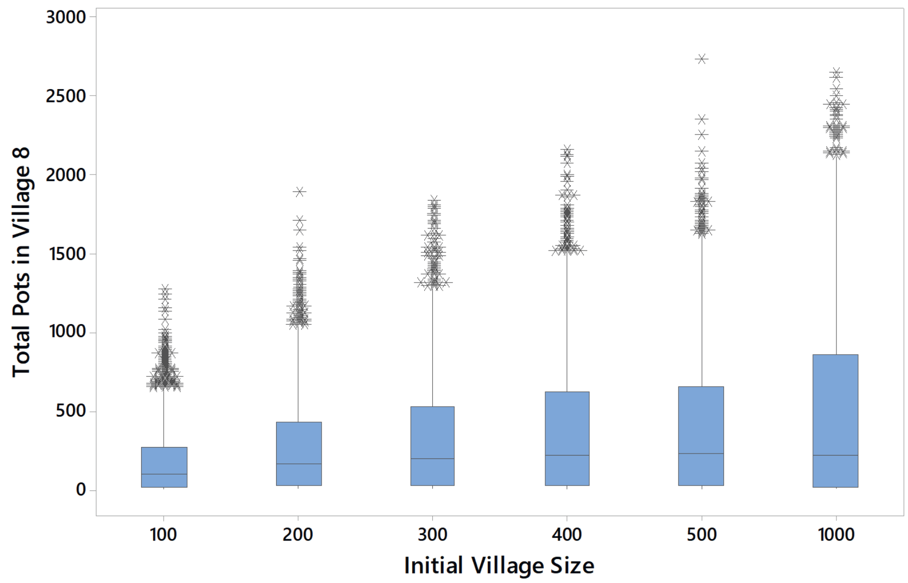

Figure 4. Boxplots showing the effect of the village-size variable on the number of vessels that reach Village 8 across all runs of the simulation.

eters to be controlled using sliders on the NetLogo interface, although, as noted above, most of these were fixed in the analyses reported here in order to keep the results simple enough to interpret. These potentially variable parameters that were not in fact allowed to vary are the number of villages (nvillages = 8); birth-probability (0.17); death-probability (0.05); the length (in NetLogo ticks, conceptually years) of the initialization period before starting the exchange (start-exchange = 100); the length of the period during which the model simulates pottery production and exchange (exchange-length = 50); and the maximum number of pots an agent will receive in a single year (annual-demand = 5).

Parameters that were varied include the average starting population of villages (village-size = 100, 200, 300, 400, 500, and 1000); how many villages away females would seek spouses (max-marriage-radius = 2, 4, or 6 villages away); the number of vessels each potter would make in a single year (annual-production = 5 or 10); and how many vessels an agent had to possess before they were willing to complete a requested trade transaction (exchange-threshold = 2, 5, or 10).

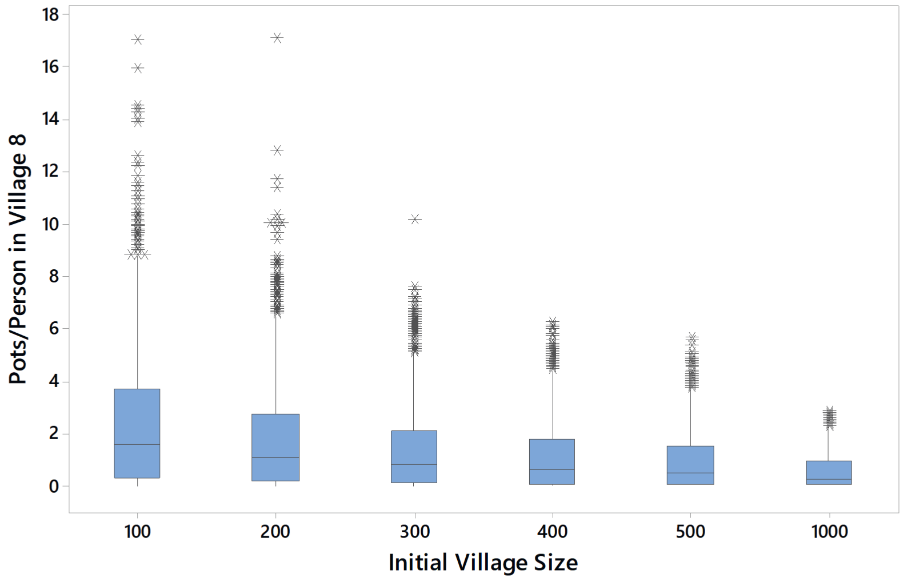

Figure 5. Boxplots showing the effect of the village-size variable on the number of vessels per person that reach Village 8 across all runs of the simulation.

For each of the six village sizes, there were 18 different combinations of the other variables, for a total of 108 different configurations of the model. Each of these configurations was run 200 times, for a total of 21,600 runs of the model. At the smaller initial village sizes the model runs relatively quickly, and computing power is not much of an issue. Larger initial village sizes increase the number of virtual individuals, kinship links, pots produced, and transactions, and require more computing resources. On a desktop computer with a 3.4 GHz Intel i7-6700 processor and 32 GB of RAM, one run of the model with the initial village size set to 100 (i.e., a total population of approximately 800) takes about 4 seconds. A five-fold increase in the initial village size to 500 (and total population to approximately 4,000) increases the run time to about 90 seconds. Completing the 3,600 runs with the population size doubled again (to approximately 8,000 total) required leaving the computer running for more than two days.

Analyzing the voluminous output is challenging, but a few trends are clear. One result of interest is how the different parameters affect the model's ability to move pots through the system. Here, production rate made surprisingly little difference. With annual-production set at 5, a mean of 329 vessels made it to Village 8 across all runs of the simulation. Doubling the production rate to 10 doubles the number of vessels in the system (approximately, because the number of vessels produced is subject to random fluctuations in population size in the producing villages), but the mean number of vessels that made it to Village 8 only increased to 341.

The exchange threshold has a larger effect, as might be expected. When the exchange-threshold variable is set at 2, a mean of 475 vessels make it to the end of the system. As the threshold is increased to 5, meaning agents are less likely to meet requests to exchange, the mean number of vessels making it to Village 8 drops to 301, and when the threshold is 10, it drops to 229.

But the max-marriage-radius variable, which controls how many villages away agents will go to find a spouse, has the largest effect on the number of vessels moving through the system. When marriages are constrained to no more than two villages away, only 15 pots, on average, reach Village 8. Increasing the possible marriage distance to four villages away results in a mean of 244 pots reaching the end of the system, and if people can go six villages away to marry, then, on average, 747 pots are exchanged to the far end of the system. As Figure 3 shows, this pattern probably results from the way marriages to spouses in distant villages create long-distance kinship links that reduce the number of transactions required to move pots across the system. Longer-distance marriages and the resulting changes in post-marriage residence effectively shorten the distance from the producing villages to the most distant village in the simulation for some agents.

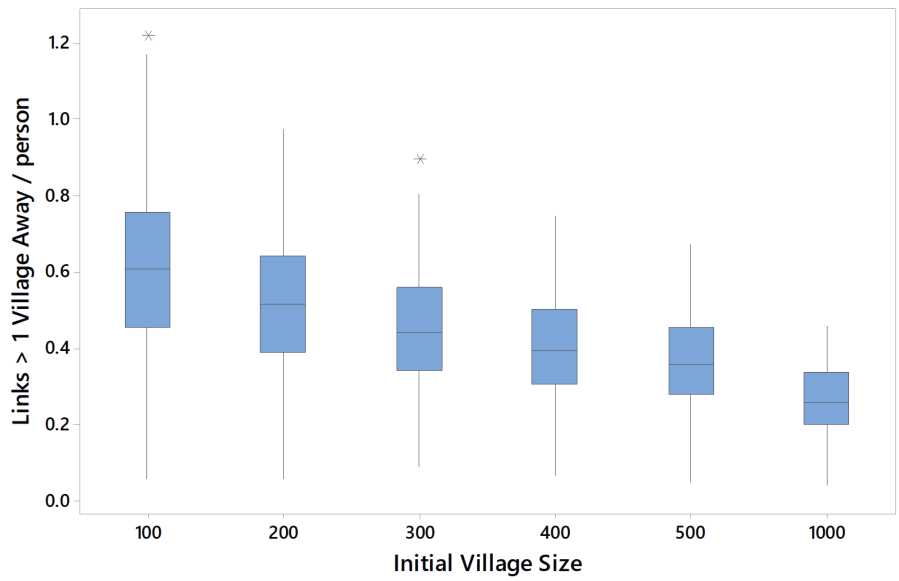

Figure 6. Boxplots showing the effect of the village-size variable on the number of kinship links created per person that are with individuals residing more than one village away.

Village size also has a strong effect. In terms of raw numbers, larger village sizes lead to larger total populations, more ceramic producers and more pots produced, and ultimately more pots make it to Village 8 (Figure 4). With village-size set to 100, on average 172 pots arrive in Village 8, while setting village-size to 1,000 allows a mean of 484 pots per run in the end village. But it may be more important to note that, when scaled to the population size, smaller settlement sizes actually work better (Figure 5). More pots per person (2.7, on average) arrive in Village 8 when village-size is 100 than when village size is 1000 (0.5, on average). In other words, it actually becomes more difficult for Village 8 residents to acquire pots when the population is larger even though the total number of pots in the village is greater.

A similar effect happens with the number of long-distance links created and is probably the reason why pots become more difficult to acquire with larger population sizes. A larger population leads to more links overall, and more outside agents' home villages, but when the number of links is scaled to population size (Figure 6), it is clear that larger settlement sizes make it less likely that a given individual will have kinship links outside their home village. Presumably this is due to the demographic smoothing of larger population sizes that make it more likely that individuals will realize the preference for marrying within their home village.

Other patterns of interest require detailed examination of disaggregated data and examination of individual runs of the simulation. These include the structure of the networks formed and the variation in outcomes for individual agents. I will focus here on comparison of two runs which differed in only the setting of the village-size variable, which was 100 in one run and 500 in the other. Max-marriage-radius was set to 6, exchange-threshold to 10, and annual-production to 10. Limited additional analysis suggests that the differences seen in these two runs are at least broadly representative of patterns that would be seen with a larger sample of runs, but much work remains to be done.

Figure 7 shows the number of pots owned by Village 8 residents at the end of each of the runs. In both cases, most of the agents have no pots. In both cases, the distribution is highly skewed, and one or two individuals possess a large number of vessels. With village-size at 500, one agent has 20 pots and another has 14. But the distribution is much more skewed with village-size at 100. One agent has 38 vessels; the next most successful traders are three individuals with nine pots each. This variation in outcomes is broadly similar to the variation seen in the archaeological examples briefly described above. Importantly, the success of the most successful individuals in Village 8 are not due to their centrality in the network; the three most successful all have average numbers of links (Figure 8). Two of them, however, benefit from very distant kinship links. Most notably, the individual with 38 pots in the village-size = 100 run was a male born in Village 2 who married into

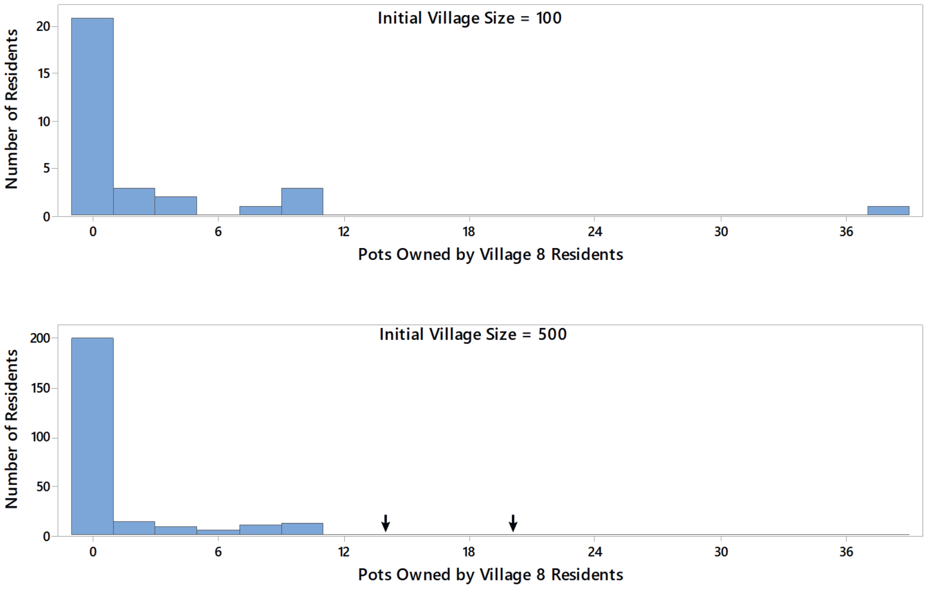

Figure 7. Number of pots owned by individual Village 8 residents at the end of two runs of the simulation with different initial village sizes. Note the difference in the y-axis scale that makes it impossible to see bars representing single individuals with 14 and 20 pots in the lower histogram.

Village 8 (Figure 9); the direct link to a producing village provided a major advantage over other Village 8 residents.

Conclusion

The model reported here is a simple attempt to understand the processes underlying the archaeological distribution of trade ware pottery in some specific cases. Like most models, this one is oversimplified in many ways. Yet it is complex enough that I have only begun to explore the behavior of the model under different conditions. Still, the results here suggest several important conclusions.

First, if most exchange is among kin (which ethnographies suggest is commonly the case in small-scale societies), then random variation in the size and specifics of kin networks can lead to large differences in outcomes. Some of the differences may be due to small-world networks forming as some individuals move to join spouses in relatively distant villages. These differences in outcomes emerge from actions of many individuals following simple rules of kinship, marriage and residence, with exchange channeled along kinship lines. Individuals may compete to succeed in trade networks, but some individuals will be more successful than others even without such competition. Finally, as settlement size grows, a higher proportion of marriages are endogamous, and fewer people have kin connections to distant villages. This may be a factor in the development of market systems or other forms of trade networks in which kinship is less important than in the small-scale societies on which I base my model.

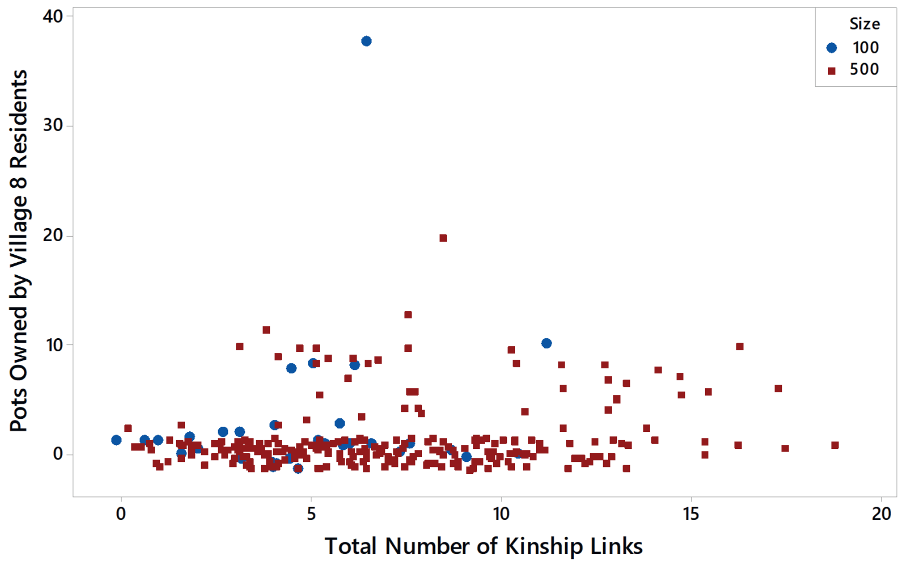

Figure 8. Scatterplot of the number of pots owned by Village 8 residents by the number of kinship links at the end of two runs of the simulation with different initial village sizes. Note that the individuals with 38, 20, and 14 pots all have average-sized kinship networks.

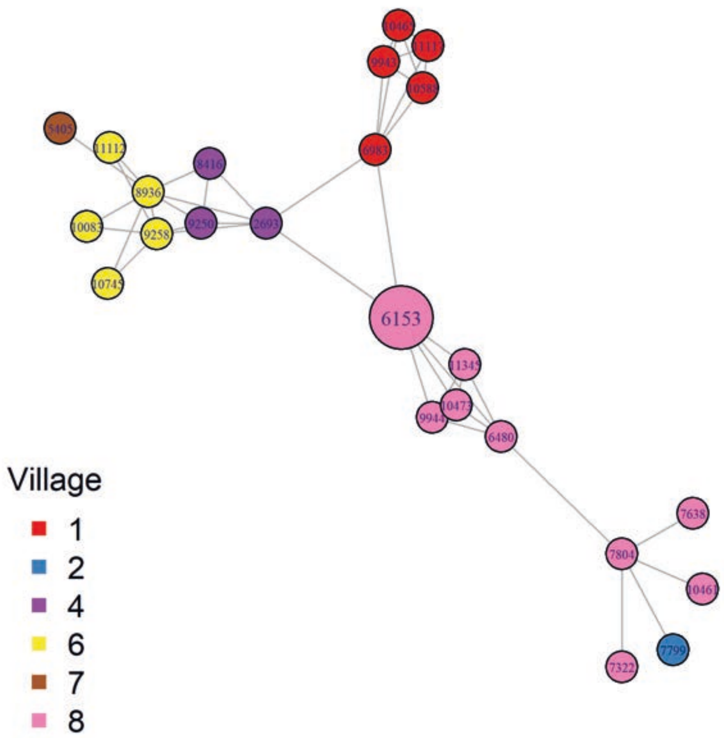

Figure 9. Network graph of the kinship links of Agent 6153, the Village 8 resident with 38 pots. The graph shows the network up to three links away from Agent 6153. Note the direct connection back to Village 1, one of the producing villages. The direct link results from the fact that Agent 6153 married into Village 8, but was born in Village 1 and still has close relatives there.

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Virtual and Augmented Realities

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From Physical to Digital, From Interactive to Immersive: Archaeological Uses of 3D, AR, VR, and More

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Abstract

The combination of improved methods and tools, widespread adoption, and continuously-falling barriers to entry has prompted the claim that we are currently living in a 'golden age of digital archaeology'. This paper provides a background discussion of the use and evolution of digital methods and tools in archaeology, as well as a summary of the conference session "From Physical to Digital, from Interactive to Immersive: Uses of Three–Dimensional Representation, Mixed Reality, and More in the Sharing and Exploration of Archaeological Data," held at the CAA 2017 conference in Atlanta.

Keywords: 3D, virtual reality, augmented reality, simulations, field archaeology, digital archaeology

Introduction: Representing a Three–Dimensional Reality

In the October 29, 1989 edition of Bill Watterson's brilliant comic strip 'Calvin and Hobbes,' Calvin approaches his father on the front porch and asks, "Dad, how come old photographs are always black and white? Didn't they have color film back then?" "Sure they did," replies Calvin's father. "In fact, those old photographs are in color. It's just the world was black and white then." He continues in this vein, declaring that, "The world didn't turn color until sometime in the 1930s, and it was pretty grainy color for a while, too." Calvin, perhaps sensing a flaw in his father's explanation, asks why old paintings are in color now, but old photos remain in black and white. His father responds that, while the artists' paintings "turned colors like everything else in the '30s," the photographs were "color pictures of black and white," and therefore remain accurate representations of the formerly colorless world. As he frequently does after these conversations, a confused Calvin retreats to the company of his stuffed tiger Hobbes and declares that "the world is a complicated place, Hobbes" (Watterson 1989).

One could be forgiven if, upon looking back through the vast majority of archaeological publications from the dawn of the modern discipline to the present, they thought the phenomenon being described by Calvin's father in the strip mentioned above was similarly applicable to this field. The exception is that, instead of just having been in black and white, the world seems also to have been–until very, very recently–in just two dimensions, as well. As Gareth Beale and Paul Reilly recently noted:

> "While the archaeological record is now primarily digital, its sections, plans, drawings and photographs are facsimiles of the analogue technologies that preceded them. This retention of analogue conventions is increasingly out of step with the general prevalence and diversity of digital technologies as mediators of professional and private life. It is also challenged by 21st-century advances towards technologies that allow for complex engage-

> ments with and representations of physical matter and facilitate the interplay between digital and material worlds" [Beale and Reilly 2017].

2D photographs, line drawings, and even the codex–based publication format of archaeological research and scholarship all (whether consciously or not) to reinforce the idea of a 'flat' past, and all pull us away from a fact that should be simple to recognize, but that we have all too often seemed to forget: the world did not exist in two dimensions, but in three (Sanders 2014: 30; cf. Emmitt et al. 2017; Richards–Rissetto 2017: 16–17; Roosevelt et al. 2015).

The advent of digital methods in archaeology in the later years of the 20th century CE began to push against this traditional manner of presenting and publishing archaeological data (e.g., Beale and Reilly 2017; Huggett 2017; Reilly 1989: 579). Innovations in digital recording have caused the amount of data collected during modern archaeological excavations to dwarf that collected only a few years before – let alone in the excavations of the previous century (Bevan 2015; Cooper and Green 2017; Rabinowitz et al. 2008). The thoughtful integration of digital methods into the process, from excavation to publication, can assist in more complete recording and, just as importantly, meaningful presentation and dissemination of these data. It is also important that data from prior excavations and campaign seasons, which may have been recorded in different formats and following different methodologies, be integrated into the overall (digital) picture.

What has been called the 'golden age of digital archaeology' (Lasaponara and Masini 2016; cf. Grosman 2016) has been furthered by the development of 3D modeling, and Augmented Reality (AR) and Virtual Reality (VR) experiences. These techniques have opened up a new horizon in excavation, data interrogation, and publication–one in which the 3D reality need not be reduced to a 2D facsimile for analysis and dissemination. These are not altogether new approaches, of course; virtual reconstructions of archaeological data were being undertaken in the 1980s (Fletcher and Spicer 1988), while by the turn of the millennium AR was being experimented with at cultural heritage sites like Olympia in Greece–although, in that pre–smartphone 'dark age,' the user had to carry an onerous amount of equipment–a bicycle helmet mounted with a digital compass and webcam, with the latter tethered to a laptop in a backpack, where the user also carried a Differential GPS (DGPS) receiver to correct for inaccuracy in GPS data, a battery good for one hour's use, a power distribution module, and wireless local network (WLAN) hardware (Vlahakis et al. 2002: 57; Figure 1).

Massive Data—With a Purpose?

The further development of digital approaches and tools, from the advent to smartphones in the late 2000s to the more recent (and rapidly–increasing) accessibility of powerful computers and 3D gaming engines like Unity, has fueled a seemingly logarithmic increase in access to, and the use of, these methods in cultural heritage fields writ large. This has spurred further advancement in the use of digital methods for archaeology, as well as more attempts to integrate digital methods and tools into data recording (e.g. Austin 2014; Ellis 2016; Uildriks 2016). However, simply gathering voluminous amounts of data for their own sake is of limited use. Instead, as Adam Rabinowitz and colleagues noted nearly a decade ago, as the exponential growth of data–gathering was under way, digital tools "make it much easier for archaeologists to interpret the results of their own work, and second–perhaps more importantly–they allow future researchers to use more data more effectively to ask new and equally interesting questions of their own" (Rabinowitz et al. 2008: 17). In other words, instead of taking what we might call the 'Sir Edmund Hillary approach' to data collection–gathering massive quantities because they are there, and because we can–there should be both a structure and a method to the madness. This might involve looking at these data in new ways, or answering (or conceiving!) new research questions, but there needs to be some purpose to it.

In the case of Augmented and Virtual Reality, one purpose is the utility they present for the presentation and exploration of archaeological datasets, primarily because of the inherently three–dimensional nature of GIS points and associated finds, and the possible shapes, models, and textures they connote (Emanuel, Morse & Hollis 2016: 8). Thus, the interaction and immersion provided by the combination

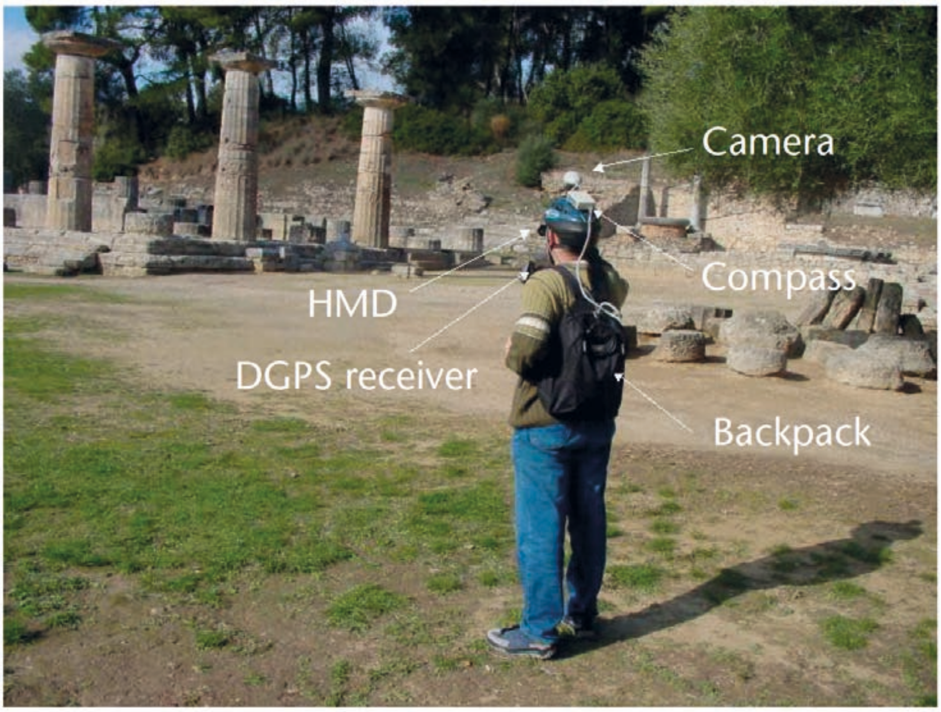

Figure 1. An early user of Augmented Reality touring the site of Olympia (after Vhlakis et al. 2002).

of 3D modeling, VR, and AR can enable two key improvements in the cultural heritage world in general, and archaeology in particular:

- Enhanced exhibition and display, which can include the digital supplements to publications and exhibits, physical reconstruction and replication, and virtual simulation of sites and artifacts, including those that no longer physically exist; and

- The close examination of live datasets, which can run the gamut from database queries to the 3D rendering of archaeological data in situ for the purpose of discovery, analysis, and information sharing.

Even recently, a common critique of 3D, AR, and VR work in archaeology has been that these approaches were "mostly aimed at enriching the tourist experience and have not yet been used to explore past experience or approach archaeological research questions" (Eve 2012: 594). While virtual exhibition is more publicly–visible and widespread, the interrogation of data sets and the development of new research questions and answers is perhaps of greater importance to the field itself. More importantly, it is the latter that will play the strongest role in influencing the future of digital methods in archaeology, as this is a field that will only continue to press forward with these time–and resource–intensive methods if there is a research–based return. Fortunately, positive results continue to be reported–to such a point, in fact, that in 2014 François Djindjian told the 42nd annual Computer Applications and Quantitative Methods in Archaeology meeting that "the very rapid development of 3D archaeology ... may possibly revolutionise field archaeology as well as all data processing that takes place following excavations and surveys" (Djindjian 2015: 4; cf. Grosman et al. 2014; Parker and Eldridge 2015: 115).

But Really ... What Do We Do With All These Data?

Communicating archaeological data in a way that can simultaneously enhance public access *and* facilitate the development of new research questions is a tricky proposition. Digital publications that include 3D–modeled objects and assemblages are an example of an interactive approach to the problem, as are published geospatial datasets and 3D–printed objects. This may be taken a step further with immersion, as AR, VR, and Mixed Reality (MR) allow for the creation of truly immersive experiences around the reconstruction, visualization, and presentation of data. I should note here the importance of noting the fact that these 'reconstructions', whether in 3D, AR, or VR, are not reconstructions at all (nor are they truly *recreations*); rather they are *simulations* of the past (Forte 2011: 8; cf. Vurpillot 2016). This term, then, will be used henceforth in this paper to refer to such virtual objects (where possible, I shall endeavor to clearly delineate between object simulations –the noun version of this term–and active simulations, or the verbal form).

VR offers a venue for digital fabrication that allows the creator total control over the 'reality' being presented. Because of this, it more fully supports experimentation with multiple definitions of 'authenticity' (Morcillo, Schaaf & Schneider 2017), or what Stuart Eve calls "possible pasts" (2012: 583). AR also supports notional fabrication, but has its own advantages, allowing users to immerse themselves not in a virtual world, but in the real world, at the physical site itself (or at a reasonable facsimile; Esclapes et al. 2013), "while visually receiving additional computer–generated or modelled information to support the task at hand" (Schnabel et al. 2007: 4). In other words, AR *enriches* the real world by adding location-based virtual components (Pierdicca et al. 2016). "The ability to move through the landscape offers us a number of different ways to cognitively involve ourselves with the environment" (Eve 2012: 592), thus giving AR an added dimension that further adds to its value for research and for the communication of cultural heritage alike.

One particular area in which AR can add value is its ability to provide archaeologists with a reconstructed picture of non–extant data. Archaeological excavation is, both axiomatically and by definition, an irreversibly destructive act. As Paul Reilly (1989: 569) once wrote, "It is an unfortunate irony that in order to reveal what lies below, the archaeological excavator must remove, and thereby destroy, what lies above. The anthropologist Sir Edmund Leach once observed that in an anthropological context, this would be rather like interviewing members from the society under study and then shooting them!". Virtual reconstruction of that which was necessarily destroyed by excavation is one method of addressing this necessary evil. While not a novel idea (e.g. Vote et al. 2002, who presented a more rudimentary approach to this a decade and a half ago), it is becoming both more feasible and more useful as visualization technologies and access to them improve (Roosevelt et al. 2015; see also below).

Ongoing improvements continues to be needed, of course, if the 3D–VR–AR approach is to become a more universally–viable method of cataloging and representing both excavations (and excavation data) and cultural heritage sites. Research efforts at institutions around the globe are pushing forward in that direction, studying and sharing approaches to things like:

1. Reconstructing excavation layers and point–find data, as mentioned immediately above (e.g., Emanuel, Morse & Hollis 2016: 8–14; Vote et al. 2002);

2. Virtual simulation, for both documentary and investigative purposes (inter alia Bernard et al. 2017; Eve 2012: 587; Liritzis et al. 2016; Manzetti 2016; Ramallos Asensio et al. 2013; Younes et al. 2017);

3. Applying GIS and landscape studies not just to geographic data, but as the basis for semiotic analysis of interactions between humans and their environment (Eve 2012; Llobera 2012; Richards-Rissetto 2017; cf. Morgan 2016)

4. 3D digitization, including high–volume workflows (Santos et al. 2017) and preservation of at–risk cultural heritage (e.g. Lecari 2016);

5. Rendering static and dynamic images from 3D scans (e.g., Counts, Averett & Garstki 2016; Galeazzi 2016; Gilboa et al. 2013; Koutsoudis et al. 2014

6. Experimenting with different methods and technical approaches to AR, VR, and data management (e.g., Chevrier et al. 2010; Balletti et al. 2015; Jiminez Fernandez–Palacios et al. 2015; Meyer, Grussenmeyer & Perrin 2007; Meyer et al. 2008);

7. Creating an interactive, immersive experience driven by avatars (e.g., Abate, Acampo-

ra & Ricciardi 2011); called 'teleimmersive archaeology' by Forte, Kurillo & Matlock (2010); and

8. Extending photogrammetry and 3D rendering for AR experiences to more complex environments, such as virtual cities (e.g., Guidi, Frischer & Lucenti 2007; Portales, Lerma & Navarro 2009).

A significant number of the publications in these areas are case–study based, presenting the technologies and workflows utilised in those cases either as one way to approach the problem, or as suitable for universal adoption (*inter multis aliis*, Altshuler and Mannack 2014; Averett, Gordon & Counts 2016; Bruno et al. 2010; Dell'Unto et al. 2016; Forte 2014; Galeazzi 2016; Jiminez Fernandez–Palacios et al. 2015; Manzetti 2016; Meyer et al. 2007; Remondino and Campana 2014). However, more widely-shared approaches remain elusive, and methods-and-tools standardization of almost any sort remains a near-impossible proposition. Ultimately, until access to funding and tools becomes more universal, and until enough institutions adopt specific methods and tool–sets to provide them with momentum in the (digital) cultural heritage marketplace, work in this space will continue to be defined, at least in part, by a form of the "not–invented–here syndrome: the conviction that 'you and I will collaborate just fine if you adopt my system and abandon yours'" (Waters 2013: 14).[1]

Experimentation with the general practices of 3D modeling, AR, and VR, on the other hand, continues to make great strides, even if the methods and workflows employed remain disparate. This is true from land to sea, where these technologies are also being used to provide better contextual understanding of shipwrecks and submerged cultural heritage sites (Costa, Beltrame & Guerra 2015). One particular example, VISAS (VIrtual and augmented exploitation of Submerged Archaeological Sites), utilises immersive VR for land–based audiences, allowing them "to live a virtual experience inside the reconstructed 3D model of the underwater archaeological site," and AR for divers who visit the site, "allowing them to have a virtual guide that provides specific information about the artifacts and the area they are visiting" (Bruno et al. 2016: 270). This is a more complex undertaking than AR experiences at land–based sites because, ironically, terrestrial tourism is in many ways a two–dimensional experience. The third dimension appears on the instrument on which the AR application is being run (smartphone, tablet, etc.), but, with allowance made for undulations in terrain, movement around the site is on the X and Y axes. In a diving environment, on the other hand, depth is also a factor, providing a Z axis that has to be accounted for in the AR experience.

Still further development is necessary to move from using virtual simulation to engage the public, to using these methods to interrogate data for the purpose of generating – and answering–archaeological research questions (cf. Eve 2012: 594). Further, though the ongoing development of virtual building and site simulations is useful and engaging, particularly for the public, "these models are too often the end product of a process in which archaeologists have relatively limited engagement" (Morgan 2009). Maria Manzetti (2016: 36), writing more recently, concurred with this assessment, and argued for a clear methodology for verifying hypothetical scenarios of 3D architectural simulations: "With the diffusion of virtual archaeology, many projects in the field of cultural heritage attempt to virtually reconstruct historical buildings of different types," she wrote. "Unfortunately, some of these [3D] reconstructions still have as principal aim to impress the external users, while the correct interpretation of the buildings modeled is much more important in the domain of archaeological research."

CAA 2017: From Physical to Digital, from Interactive to Immersive

Concerns about imbalanced (though improving) access and the lack of generally–accepted standards for tools, methods, and workflows having been noted, it appears that the state of the field in 2017 can be

1 A relevant example of this is the Unity gaming engine, which has proven to be a low–entry–barrier method for developing software that can be published across AR, VR, and web–based platforms. A potential model for interoperability is the International Image Interoperability Framework (IIIF), a hundred–institution consortium using shared APIs, rather than proprietary software and workflows, to share digital visual material (http://iiif.io; Snydman, Sanderson & Cramer 2015; Emanuel 2018a).

described as both *emergent* and *alive with discovery*, as the adoption curve of digital methods in general–and 3D, AR, and VR in particular–continues to surge. Evidence of this can be seen in the papers presented in the CAA 2017 session *From Physical to Digital, from Interactive to Immersive: Uses of Three–Dimensional Representation, Mixed Reality, and More in the Sharing and Exploration of Archaeological Data*. Themes of this session included example approaches and workflows for data gathering and processing, experimentation with standards for photogrammetry and 3D modeling, geographic analysis, virtual reconstructions of excavation layers, assemblages, and fixtures, and virtual simulations of original constructions.

A noteworthy presentation on the topic of virtual simulations was given by Daniel Löwenborg of Uppsala University, Sweden ("Augmented History – A Virtual 'Window to the Past'). This paper focused on a detailed, interactive 3D simulation of Old Uppsala (Gamla) in the mid–6th century CE, complete with buildings, graves, and animated characters to provide a more complete look not just at architecture, but at life in the Old City. Animated characters were exchanged for avatars (cf. Morgan 2009 and Forte et al. 2010, cited above) in a virtual simulation of the Sanctuary of Hercules at Deneuvre in Eastern France ("Making Virtual Reality Real: What Can We Learn by Bringing Together Virtual Reality and Visual Attention Analysis?"). Damien Vurpillot presented on the utilization of avatars to create interactive scenarios within the sanctuary, and the tracking and quantitative measuring of these users' movement through the landscape – a study conducted in hopes that the trends seen here could serve as a starting point for the development of virtual reality as a research tool. Visitor movement through a site was likewise addressed by Bonna Wescoat and Arya Basu, from Emory University ("On the Dynamics of Interactive Exploration over Animation as Methods of Experiential Simulation in the Sanctuary of the Great Gods on Samothrace"), who utilised 3D modeling of the site of the Great Gods at Samothrace to provide an immersive experience in the physical environment, and to focus on the movements and sensory perceptions of pilgrims visiting the site at the time of its use, including how the nexus of terrain, buildings, and movement heightened the experience of initiation into this cult.

Experimentation with high–quality photogrammetry continues to be a key topic in discussions of 3D modelling, VR, and AR. Ivan Rudov of Siberian Federal University, Krasnoyarsk ("Combined method of 3D model of archaeological objects optimisation for a mobile app") offered the session the results of his own workflow experimentation for static and real–time mobile visualization of photogrammetric models, which provided realistic models with high texture resolution. High–resolution photogrammetry that requires few enough computational resources to properly render in a live mobile environment has become increasingly useful to practitioners and those seeking to interrogate the raw data with the wider adoption of attempts to virtually reconstruction of *excavation levels* themselves (cf. Vote et al 2002: 42). As addressed above, archaeological excavation remains destructive act that is physically irreversible. However, if data are properly gathered throughout the excavation process, such destruction may be reversible in *digital* form.

Two papers in particular addressed the representation of excavation phases in 3D, AR, etc. Luke Hollis of Archimedes Digital ("MorgantinaVR: Cityscale Handheld AR and CrossPlatform VR for Visualizing Georeferenced Datasets") reported on the modeling of excavation strata the Contra Agnese Project from Morgantina, Sicily, where they continue to develop the ability to virtually browse day–by–day recreations of trench models and 3D renderings of the datasets associated with CAP's museum (cultural heritage) and geospatial teams. Similarly, Bryan Burns and Jordan Tynes of Wellesley College ("Excavation Progress and Artifact Manipulations in a Virtual Environment"), created 3D models in the Unity game engine to record and reconstruct excavations of early Mycenaean tombs at the site of Eleon in Boeotia (Central Greece). Imagery gathered by drones was converted into photogrammetric models, which could be utilised to track daily progress and to allow for analysis at various points throughout the excavation. They also coupled virtual models with interpretive tools to enable users to interact with finds from the site. A slightly different tack on research and data interrogation was taken by a team from HTW Berlin, represented by Sebastian Plesch, whose presentation provided an overview of a collection of packages designed to support the exploration and examination of 3D archaeological assets in interactive Virtual Environments ("VR:TA – A Virtual Reality Toolset for Archaeologists"). Using the Temple of the Storm God at Aleppo (Kohlmeyer 2009) as an example, Plesch highlighted two particularly useful VR:TA packages: the measurement tool, which can create detailed measurements of 3D assets at multiple scales, and the sky tool, which can allow researchers to adjust the virtual night sky so that the correct constellations and planets appear for the date being presented in the reconstruction.

The open discussion portion of the session provided energetic conversation about tools, workflows, and other approaches to incorporating computer applications and digital methods into field archaeology in particular, and cultural heritage in general. Among the most generative topics was that of connection and collaboration: how contacts can be made, and bridges built, across the appropriate specialties, both within and across institutions. The value of Digital Humanities centers and other on-campus organizations as matchmakers or clearinghouses for collaborative projects was raised, although not all centers operate in this way, and many institutions lack them altogether. The importance of collaborative effort across a range of fields (along with the value of CAA's interdisciplinary membership) was exemplified during the discussion of virtual simulations, as a structural engineer in attendance was able to speak to the value of having an expert in that field as part of the team to consult on the real–life efficacy of virtual designs, much as Manzetti (2016, noted above) rightly called for archaeologists to be involved in the same due to their own expertise. The discussion concluded with general agreement about the importance of building those bridges, and reaching out to those in computer science, engineering, and other relevant academic specialties who can add needed expertise in their field to archaeological and cultural heritage projects.

Conclusion

Archaeology as a discipline is very much in the throes of methodological change: digital methods are becoming more prevalent, tools for data gathering and synthesis are becoming more widespread and interoperable, and the financial and technical barriers to engaging in digitization, and in digital reconstruction and simulation, continue to recede. We may indeed be in the midst of a 'golden age of digital archaeology,' as Rosa Lasaponara and Nicola Masini (2016) described the current period; however, there remains much more to be done, lest the so-called 'digital archaeology' of the present emulate the 'virtual archaeology' of the 1980s, and fail to live up to its remarkable potential to change the way we do business altogether. Modern digital tools and techniques offer far more potential than their 'virtual' predecessors: while the latter was used to describe "the way in which technology could be harnessed in order to achieve new ways of documenting, interpreting and annotating primary archaeological materials and processes," we have now grown into a technological world that "allow[s] for complex engagements with and representations of physical matter and facilitate the interplay between digital and material worlds" (Beale and Reilly 2017: 1).

Much as those who first set sail in the Age of Exploration did not know what lay ahead, and could only learn it by venturing out themselves, we cannot yet know what (or how many) new research questions will arise as the result of three-dimensional site representation. Nor can we yet know what new understandings may be gained from virtual simulations of sites the world over. We can, however, be certain that such discoveries will, at some point, require a shift in thinking about the past itself. For too long, our study of archaeology and of history have been mired in a two-dimensional past. The tools and methods for gathering, analyzing, and communicating voluminous quantities of archaeological data are available and in use; however, while Virtual Reality, Augmented Reality, simulated reconstructions, avatar-based interaction, and more promise a combination of entertainment, interactivity, and illumination, the most basic advantage of the modern digital age is its promise of finally providing the past with what it has needed all along in order to be properly represented, studied, and understood: its long-missing Third Dimension.

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MorgantinaVR: Cityscale Handheld AR and Cross–Platform VR for Visualizing Georeferenced Archaeological Datasets

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Abstract

The use of Augmented and Virtual Reality in cultural heritage has increased dramatically in recent years, with uses that go far beyond creating and displaying digital reconstructions for museum visitors and tourists. This paper describes the collaboration between Archimedes Digital and the Contrada Agnese Project (CAP) to develop a framework and suite of applications to support the examination display of archaeological data from the site of Morgantina, Sicily in VR and AR. Primary purposes of this digital approach include facilitating collaboration between CAP's specialists (archaeological, geospatial, and museum), and enabling the effective dissemination of data to researchers and to the general public.

Keywords: augmented reality, virtual reality, cultural heritage preservation, geospatial data visualization

Introduction

Though it may appear as though the emphasis on the digital is a sudden development in archaeological fieldwork, data analysis, and cultural heritage management, the phenomenon is not as new as it seems. As early as the 1980s (now nearly four decades in the past), the impact of digital methods on the collection, interrogation, and representation of archaeological data were being considered: virtual reconstructions (in C!) were being undertaken (Fletcher and Spicer 1988), while "computer database systems, high–level graphics systems, and artificial intelligence techniques are already beginning to allow archaeologists to ask new types of questions and to look at their data from positions which were previously impossible" (Reilly 1989: 579).

By the end of the millennium scarcely a decade later, augmented reality (AR) was being utilized at some historical sites (e.g. Vlahakis et al. 2002), and the applications of virtual reality (VR) to archaeology were becoming increasingly discussed at conferences and in publications (e.g., the papers in Barcelo, Forte & Sanders 2000). At that time – still a few years before Steve Jobs unveiled technology that would quickly place the computing equivalent of a Cray supercomputer in the palm of virtually an entire population's hands – attempts to provide a mobile AR experience were far more unwieldy. One example, which was first tested at Olympia, was called ARCHEOGUIDE (Augmented Reality–Based Cultural Heritage On–Site Guide). ARCHEOGUIDE utilized a PC, a differential GPS (DGPS), and portable units (laptop, pen–tablet, or palmtop) to provide a mobile experience. However, the user then had to carry a significant amount of gear with them to drive that mobile experience. For example, for the laptop-based version of the experience, "the user [wore] a bicycle helmet with a USB Web camera and a digital compass mounted on top, and a backpack containing the laptop, DGPS receiver, battery, power distribution module, and WLAN hardware" (Vlahakis et al. 2002: 57, especially Figure 7). For the pen–tablet, the user could forego the bike helmet and backpack, but still had to carry a hardware box under the tablet, as well as a battery in shoulder–slung case (Vlahakis et al. 2002: 58). In light of this, and in absence of the prescience necessary to see the smartphone revolution looming just around the temporal corner, it is perhaps unsurprising that one of the major needs identified by the ARCHEOGUIDE project team was "the development of custom–made mobile devices that are compact and lightweight enough to carry around outdoors" (Vlahakis et al. 2002: 59)!

That revolution, and the proliferation of mobile devices that it spawned – first smartphones, then tablets – spurred further advancement in the use of digital methods for archaeology, as well as more attempts to integrate digital methods and digital tools into data recording (e.g. Austin 2014; Ellis 2016; Uildriks 2016). The new world of mobile devices has provided archaeologists and users alike with the piece that the ARCHEOGUIDE team was missing two decades ago, while the increasing rapidity with which more and more complex computations can be carried out has allowed for nearly continuous improvement in the level of graphics and environmental interaction that can be provided to the user of an AR or VR experience.

At the same time, the sheer quantity of data being gathered during an archaeological excavation (and during post-excavation analysis) requires a computational approach that can render those data meaningful not just to a technical whiz working part-time on the project, but on an as-needed basis to any member of the broader team, whether their focus is on the archaeological, on the geospatial, or on museum-based cultural heritage. The collaboration between Archimedes Digital and the Contrada Agnese Project at Morgantina, Sicily, which is the focus of this paper, centers on that combination of services and features: the development of data workflows that allow for cross-team access, and the development of VR and handheld AR applications for rendering both excavation data and notional reconstructions of buildings on site.

Archimedes Digital + the Contrada Agnese Project: Introduction

In the summer of 2014, a team of engineers and developers from Archimedes Digital (AD)[1] began working with the Contrada Agnese Project (CAP)[2] at Morgantina, Sicily to investigate the possibility of effectively visualizing and interpreting archaeological data in virtual and augmented reality. A major goal of the AD–CAP partnership was throughout this development has been to explore the optimal methods for integrating archaeological, geospatial, and museum data in the digital environment, both during initial field work and in the publication and dissemination phases of the Morgantina excavation (Figure 1). This project was the technical corollary to an effort on CAP's part to best support integration and collaboration, both in the field and during post–excavation artifact and data processing, by archaeologists, conservators, and other specialists (Smalling et al. 2016). Prior to AD's involvement, CAP had been developing a comprehensive collections database (the Morgantina Legacy Data Integration project; Lieberman et al. 2014), which CAP sought to make accessible to team members, researchers, and the general public.

CAP and AD built on the Morgantina Legacy Data Integration project by joining geospatial information systems data with museum records and 3D photogrammetry data. This was accomplished via a small network of connected data services which cleaned, processed, and transformed the data into a sharable standard that could be used across platforms, including web, mobile, and desktop applications. The 3D applications utilized the Unity game engine for visualizing data, because it was the easiest way to develop software that could grow and adapt to publish across VR, AR, and web-based solutions interchangeably.

As AD went about establishing these services, though, there emerged a persistent divide between the solutions being implemented (which were largely web–based at the time), the data that the CAP excavations team generated, and the landscape and context in the field, where the data were actually being discovered. This began to change in 2015, following the release of a new wave of consumer–grade hardware for mobile virtual and augmented reality devic-

1 The project team included Luke Hollis and Aden Brown (Archimedes Digital), Elliott Mitchell (Vermont Digital Arts), Jarien Sky–Stutts, and Jess Winter (Misc. Labs).

2 The CAP team was led by Alex Walthall, Assistant Professor of Classics at the University of Texas, with geospatial and data teams consisting of James Huemoeller, Adjunct Professor at the University of British Columbia and partner at JIM architecture, and Leigh Liebermann and Ben Gorham, PhD candidates at Princeton University and the University of Virginia, respectively.

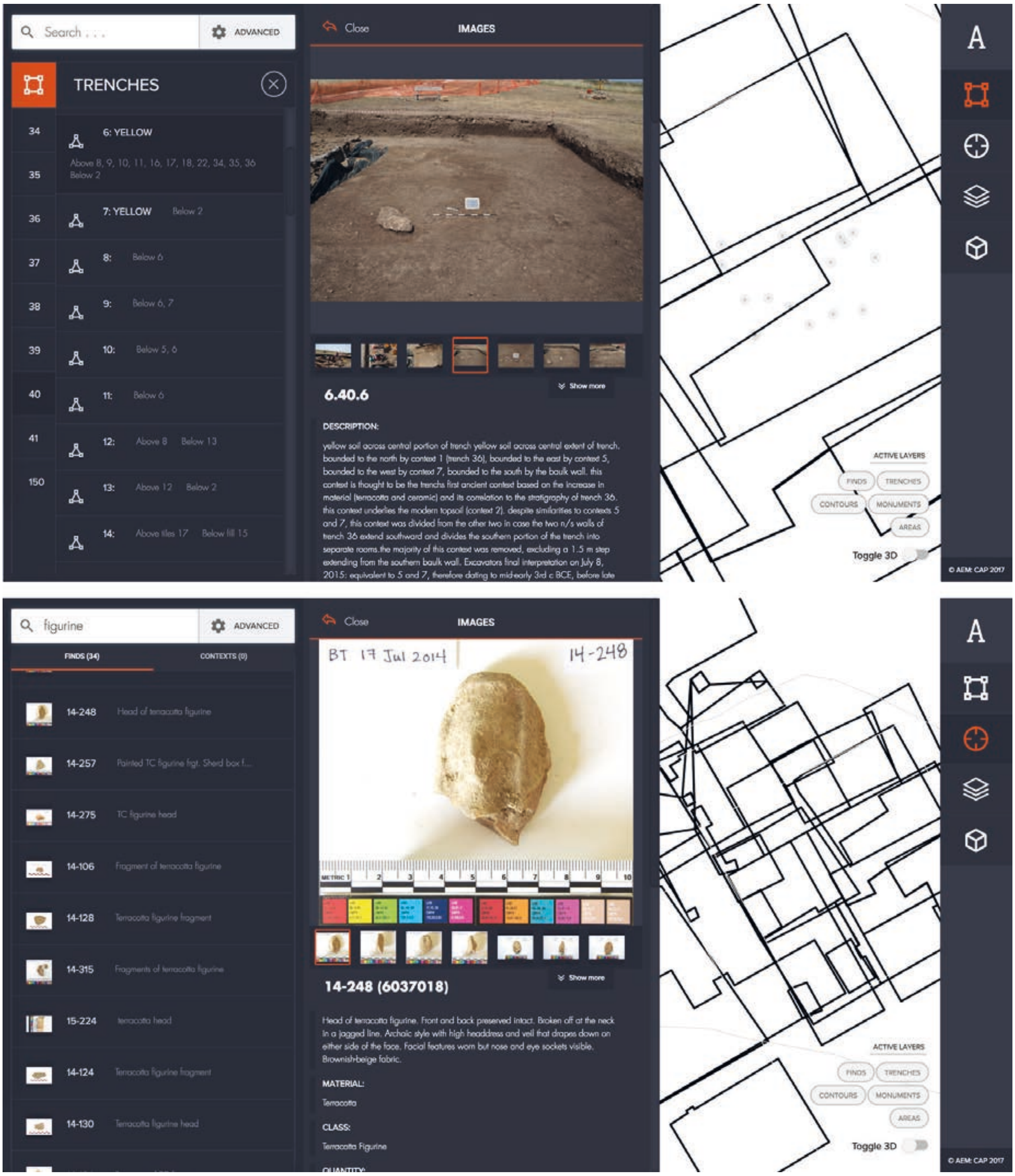

Figure 1. Data from the GIS and museum collections, Filemaker databases, and other services displayed on the CAP data integration and presentation website.

es, such as the Project Tango augmented reality hardware, as well as widespread adoption of the GearVR and Google Cardboard headsets for mobile virtual reality.[3] The team was interested in exploring the optimal platform(s) for three uses in particular: in active field excavations, at museums that dealt with the content, and in classroom–based educational experiences. The project was initially drawn to Project Tango for querying and interpreting archaeological data in the field in AR. However, because the Project Tango software development kit (SDK) required specialized hardware in the smartphone or tablet that it was to be run on, we eventually expanded the mobile

3 Project Tango was released in June 2014 by the Google Advanced Technology and Projects group. The platform was retired in March 2018 in favor of ARCore, Google's new platform for building augmented reality experiences (https://developers.google.com/ar/discover/).

Figure 2. Google Project Tango screenshot showing the integration of 3D GIS and the Morgantina collections database.

Figure 3. Example usage of the augmented reality application on site at Morgantina to explore architectural reconstructions of the agora in 211 BCE.

applications to include, as of this writing, most mainstream AR and VR platforms.

The value of the project on any platform was continually judged by its ability to leverage multiple data sources and types in a 3D environment using the Unity game engine. These data sources and types included the GIS database (PostGIS, a spatial database extender for PostgreSQL), photogrammetry, and museum collections data. In other words, work was evaluated first and foremost based on how well it communicated the CAP geospatial, museum, and photogrammetry data at varying layers of interpretation. In the initial stages, we focused on visualizing all of the "finds" data (the location data on objects themselves) from the GIS database. This was joined with the museum collections records for those finds, and with an image or images of the find (these were hosted on Google Cloud Platform Online Data Storage) (Figure 2).

In a later phase, the team began to focus on 3D reconstructions of monumental architecture in the agora at Morgantina, so that they could be used as educational or interpretative tools in AR for visitors to Morgantina and in VR by users located elsewhere (Figure 3). For these conjectural 3D reconstruction models, we hoped to be simultaneously experimental and pragmatic in refining our method for future work that will be used during future excavation seasons and in the classroom.

Archimedes Digital + the Contrada Agnese Project: Technical Background

During initial stages of development, a primary goal was creating an interoperable service for exposing geospatial data from the geographic information systems (GIS) database maintained by CAP via the open–source QGIS software (Figure 4). To this end, the team created a small service that monitored shapefiles on a local server on site at the CAP. Whenever a shapefile was updated, the service ex-

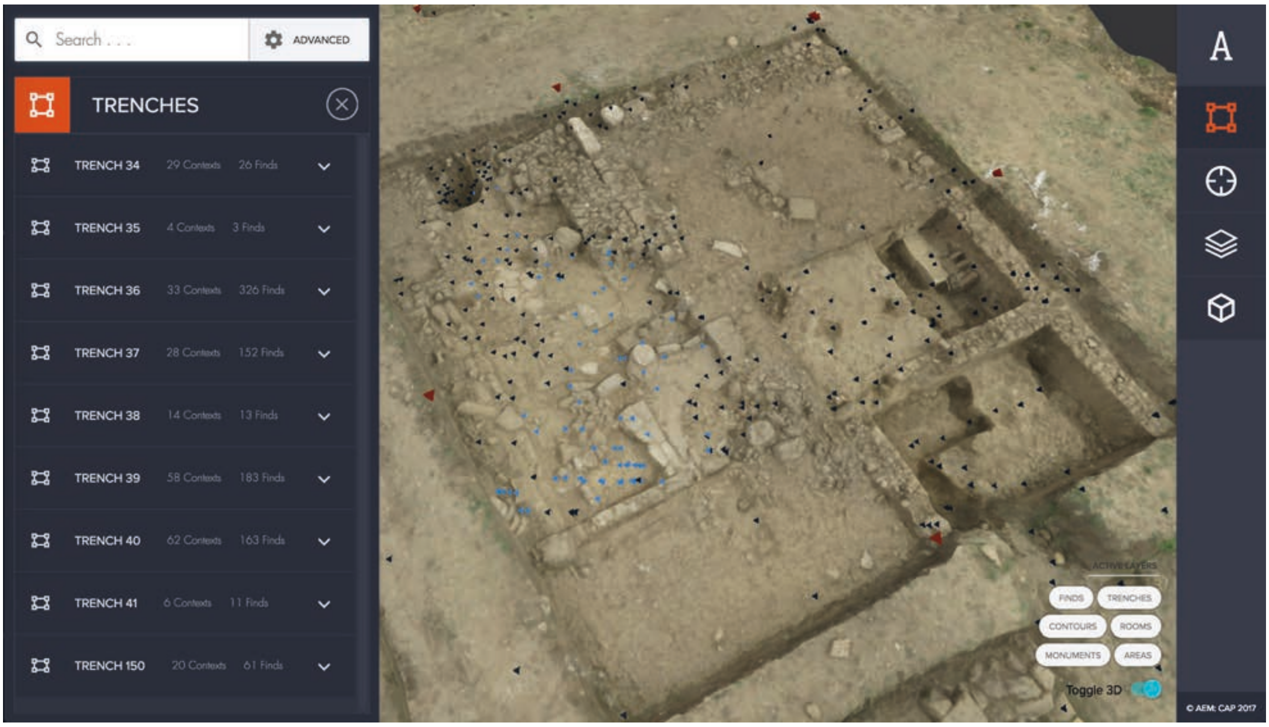

Figure 4. An example of the 3D geodatabase visualized with Unity on the CAP data website, alongside a georeferenced photogrammetric model of the excavations.

tracted its contents to GeoJSON. These were stored in a PostgreSQL database with PostGIS and served via the GraphQL Application Programming Interface (API) query language, which we adopted as a simple standard for sharing data between applications. This API was paired with an API from the project's collections database to create a minimal data presentation layer that our Unity applications could use to visualize object records from the collections and geospatial databases in a 3D environment that we adapted to VR and AR platforms as well as a traditional interpretative website and mobile application.

In order to display geospatial data in the Unity game engine, the AD team created a content management system for curating AR experiences while in the field. This allowed a reference point to be added to the Project Tango Area Description Files (or the GPS and compass readings in smartphones) to position a mobile device appropriately when starting the app onsite at Morgantina. Specifically, the content management system back-end includes a map–based interface and similar GraphQL API to the geospatial service to inform the Unity application of its real-world position in the context of the project's services-data presentation layer. On a conventional modern smartphone, the device requests information at runtime from its geolocation sensor data. After the GPS sensor reaches an accuracy threshold of 10 meters, the camera in the Unity scene is moved into the proper position relative to the internal coordinate system.

Orienting the device to its position in relation to the globe has always been a difficult issue, and that continues to be the case. We have found that the accuracy level of GPS sensor data in conventional smartphones continues to be one of the major blockers of any mobile AR application (at least, any that is more sophisticated than 'Pokemon Go'). At Morgantina, fortunately, the mobile AR application was primarily used to visualize architectural reconstructions of large buildings in the agora. As these buildings tended toward hundreds of meters in length, smartphones' 10-meter accuracy offset did not present as much of an issue. Ultimately, the team decided that whatever the application lacked in to–the–meter accuracy (in terms of placing the building reconstructions directly on those buildings' extant foundations) was more than made up for by the visualization itself, which allows site visitors to view the architectural remains that are present in the agora as they may have looked at the time of their use.

Conclusion and Future Prospects

Following the 2016 field season, Archimedes Digital's work has focused on adapting existing 3D assets for two uses: continued virtual reconstruction of the agora and stratigraphic presentation of the excavation trenches. This is being optimized for VR experiences to create an enhanced reconstruction that features props and educational interactive materials, with the HTC Vive and Oculus Rift being targeted as primary platforms for use. On higher–end desktop VR platforms, we have been able to factor in higher–quality photogrammetry of finds from the Contrada Agnese Project's collections database, such as terracotta figurines, ceramics, architectural fragments, altars, grain mills, and other objects. Development of the Morgantina VR and AR applications will continue, following the guidelines developed from our previous exploratory prototyping, as will continued support for CAP's data services and forthcoming website. In early 2018, we hope to launch production AR applications that will be available for Android and Apple smartphones on the Google Play and App Stores, respectively, while CAP and AD will collaborate closely in the summer of 2018 to integrate AR into the workflow for active excavations.

The Vive and Oculus Rift versions of the Morgantina reconstructions in particular have been geared toward the classroom educational experience, with a first integrated use planned for an archaeological survey class in Spring 2018. To support this educational use, AD will focus on developing the Vive application in particular to include further interactive assets, including variations in architectural reconstruction. An essential element of planned classroom use is a quest–based exploratory learning experience that allows students to view between five and ten different alternatives for the reconstruction of a given building. This tool will allow students to evaluate each alternative reconstruction, based on its merit and relative to a few salient features, such as the archaeological record, the architectural style in use at that time in Sicily, and general knowledge of building materials available at the time of construction. We intend to set up a HTC Vive running the application in a lab that will be accessible to students so that they may complete a session with the application on their own time and terms.

As noted above, more institutions, organizations, and researchers exploring the AR, VR, and 3D space may mean more fragmentation in terms of methods and approaches, but it also means that all can benefit from the constantly–ongoing development of workflows and testing of technologies. Archimedes Digital, and the AD–CAP team, continue to benefit from researchers and technologists working on similar software applications for archaeological data presentation across web, mobile, and AR/VR platforms. While the use of AR as a tool for tourism also continues to grow (e.g. Vhlahakis et al. 2002; Fritz et al. 2005; Kounavis et al. 2012; Yovcheva et al. 2012; Linaza et al. 2014), the immediate future of Archimedes Digital's work in archaeology and at archaeological sites is expected to continue prioritizing education, research, and other scholarly use cases first, and tourism for the general public second.

Through all of this, we plan to continue contributing both to archaeological practice and dissemination, and to the wider web of developers and practitioners who will continue to benefit from open-source development and applications like those in use at Morgantina.

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Quality vs Quantity: Advantages and Disadvantages of Image-Based Modeling

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Abstract

In the last few years, survey has changed radically thanks to progress in the field of 3D, massive data acquisition methods. The scientific debate focuses on the control over data quality by comparing Structure from Motion acquisition methods with consolidated methods. Collecting and interpreting a large amount of information helps us deeply understand our cultural heritage. This system of knowledge that we create has to achieve a dual objective: to document heterogeneous data with guaranteed repeatability and to ensure data quality during data capture and model processing. This information includes cultural resource data: dimension, information on construction, material characteristics, color; etc. The case study, the Abbey of Santa Maria della Matina, focuses on the shift from quantitative data, acquired in a semi-automatic manner, to qualitative data, controlled under uncertainty. In this framework, all branches of the "Science of Representation" ensure metric, spatial, and formal control of the built models.

Keywords: integrated survey, models, color, scale

Introduction

Every organism of architectonic heritage is a complex system that embraces interlinked tangible (material) and intangible (non-material) values which equally contribute to its overall value. In order to grasp its "essence," it is necessary to study it properly, carry out enquiries that go beyond its exterior aspect and include its significant (constituent) elements. In other words: it is necessary to survey it. Indispensable in achieving this objective are all the surveying activities directed towards generating a deep knowledge[1] of the artifacts and features being studied. Taking into account the cultural significance of the object of study and having subjected it to observation and proper cognitive processes, the surveyor enters into a dialogue with the structure so that it becomes possible to preserve it correctly and communicate its value (Docci and Maestri 2009). Knowledge is propaedeutic for the evaluation and preservation of cultural heritage, both of which are intimately related with innovative technologies in all the stages of the preservation process: acquisition, management and sharing.

Nowadays, observing how this process is tackled, we can only conclude that the instruments of massive acquisition, digital representation, the use of systems of fast communication of raw data and 2D/3D models have become almost the only vectors for the study and communication of the architectonic and archaeological artifact. Technological developments of the last two to three decades has profoundly changed the process of knowledge generation. While the contri-

1 Whenever in the course of their evolution human beings confronted complex phenomena, they invariably sought to develop strategies which enabled them to overcome the limitations imposed by their senses. Descartes demonstrated clearly that this involves two different kinds of knowledge: the common-sense knowledge (which we acquire through experience) and the profound knowledge that can be reached solely by methods and techniques exclusively related to the mind and which are beyond the capabilities of our senses.

bution of the scholars at each stage of cognition must be considered indispensable, it has become evident that the new instruments have transformed surveying operations into semi-automatic procedures capable of gathering millions of points at a low uncertainty level. The phrase "digital building recording technologies" leads us to a relevant gathering of data that are accurate and efficient, but until now the measurable aspect of a building cannot be considered exhaustive for its cognition. Hence, the necessity to study the dichotomy between quantity and quality of the data inherent in every survey carried out with instruments of massive acquisition. While the term "quantity" refers to physical parameters, coordinates, positioning and geometry, all of which define the artifact, "quality" describes its contingent or permanent properties, the formal aspect concretely determined. The control over data "quality" is connected with the set of parameters which define the measuring properties: precision, uncertainty, repeatability, accuracy (Yasutaka and Ponce 2009; Ippolito and Bartolomei 2014). Quality is also involved in the capacity to consider all the aspects of the artifact that make a better understanding of its intangible values (chromatic, material, those concerning its preservation and its context).

Acquired information considerably improves qualitatively when we integrate diverse methodologies, considering that each of them fills in the gaps left by others. While the research objectives are various, they rest on the profound knowledge of an architectonic complex, deeply stratified, whose complexity will be enhanced through a synthesis of digital models with a correct interpretation and management of information. Specifically, the enquiry will be oriented towards an analysis of the quality of the data acquired massively, ranging from the urban scale to that of the architectonic detail. The other fundamental aspect of the study, after years of consistent use of the laser scanner, which is a high cost surveying instrument, is to compare it with the results of using low cost acquisition instruments (with the use of open source software at the stage of elaboration rather than the paid variety) in order to test the level of detail that is possible to achieve in terms of metric accuracy as well as metric, chromatic, and surface information[2].

2 The comparison between high cost and low cost survey instruments is possible because they give analogous result in terms of models (numerical model) and edit operation to construct mesh models. In fact, for some years, SFM allows a user to get analogous results as 3D laser scanner for just the cost of a simple camera.

Reflections on the Surveying/Survey Operations

A few decades ago, any consideration of cognizing a cultural artifact had to take into account a series of limitations inherent in the traditional instruments applied as well as the long time it took to acquire information. The consistency of data gathered often proved to be insufficient and inadequate to obtain results that were scientifically valid. The construction of the model was the fruit of a series of attempts when the discontinuities to be measured were selected prior to starting the acquisition operations. Nowadays, the continuous advances of technologies and the development of ICT (Information and Communications Technology) offer innovative instruments, updated and improved in a short time span, that are more economic and faster, more easily applicable for scientific research for the acquisition and subsequent elaboration of models.

Even though the density and accuracy of locational data acquired through 3D scanning or SfM reduces the danger of a subjective interpretation, it should be understood solely as a starting point for subsequent, in-depth analysis. The analytic phase of data acquisition and gathering of any information that can serve to increase the knowledge of the object under study adds to the complexity of 3D surveying (Chih-Heng et al. 2010). The "baggage" acquired, which at this point emerges solely in its quantitative aspect, should assume a qualitative value. In order that the final quality of the model is not compromised, one must adopt a critical standpoint at the stage of massive data acquisition and pose questions on fundamental aspects, like resolution, accuracy, precision, and evaluate all the parameters accurately, such as: the choice of the instruments, the characteristic features of the object surveyed, distance, sample spacing, etc.

The subsequent stage of the survey, understood as the process leading to the construction of models, constitutes a qualitative operation carried out with the view to deepen our knowledge of the artifact and is rooted in the quantitative component of the massive data acquisition (surveying). Nowadays, surveying methodologies and techniques enable us to capture millions of points on architectural surfaces and link those points to the scale of the models to be constructed (Wojtas 2010). Hence the survey is responsible – through the construction of 2D/3D models, for the representation of all the characteristics extracted in the process of surveying. Thus, the survey emerges as a cultural process, which identifies distinctive characteristic elements and initiates the process of selection; albeit with a great number of objective data at the point of departure and a through interpretation of the critical capacities of the operator.

The use and integration of the instruments for massive point acquisition has reversed the ways of selecting and measuring done traditionally: the significant points are now selected after having been acquired (Docci, Bianchini, & Ippolito 2011). The construction of the object obtained directed towards the profound knowledge, to use Descartes' terminology, of the edifice to which it corresponds, is by no means co-related only with the great quantity of points gathered but also to the quality and type of information and its correspondence with reality. The result of the process will depend on the equilibrium struck between the quantitative component, related to the abundance of data acquired in the course of surveying, and the qualitative one linked to the choices critically decided upon at the stage of elaboration and leading to the construction of the survey, in accordance with the principle of data irrefutability[3]. If the result obtained passes the falsifiability test, we can consider it to be scientific.

In this manner 2D/3D models contain more than metric data, namely other heterogeneous information of equal or even greater relevance to the purpose of protecting and preserving Cultural Heritage. Among them we can count the information on construction aspects, identification of possible modifications introduced in the past, characteristic features of the materials, the color, the state of preservation, etc. The principal objective is to establish a bijective correspondence between the real object and its model, reducing the complexity of numerous multidimensional data acquired and synthesizing them within the very model that will describe reality through geometric entities, like points, lines and surfaces. Apart from being suggestive of reality, the 3D model must be the fruit of an intelligent activity of selecting variables that are capable of communicating the artifact on the basis of predetermined goals (Bianchini, Inglese, & Ippolito 2016).

We can conclude, therefore, that constructing qualitative models is based on the principles of the method that can be considered practical and theoretical at the same time and which finds corroboration in the rules of René Descartes' "Discours de la méthode" (1637).

These rules, defined as evidence, analysis, synthesis, enumeration, and revision can be considered stages in the process directed towards the scientific construction of a model where the passage from objective to subjective data inevitably transforms quantity into quality. This set of procedures can be defined as the starting point for structuring out a critical operative method that will lead to the representation of the artifact, taking into account the objective component acquired preliminarily. Acquisition of data conceived as measures, and of metadata, conceived as information on the process, must be carried out in accordance with the uncertainty level adopted. The various data must then be archived accurately and shared so that they became easily accessible to all members of the scientific community.

Even though nowadays the surveying and survey operations are realized almost exclusively with digital means following a pre-established sequence, what is often missing from the operative practice is the complete and reasoned out standardization of processes. This would make it possible to fix quantitative and qualitative features of objects analyzed in relation to the methodology applied as well as to the scale of models. Hence, it is a correct approach to take into account the structure and quality of data in accordance with their limitations and potentialities but also with their ability to superimpose and complement each other in order to provide a digital database containing heterogeneous elements in an organized manner.

3 The principle of falsifiability is the criterion formulated by Karl Popper (Reale, Antiseri, & Laeng 1986) for differentiating controllable theories from the non-controllable ones. This particular interpretative model is based on the error in which the truth emerges as the fruit of scientific progress characterized not by accumulating certainties but by progressively eliminating errors. According to the falsifiability criterion, a theory – in order to qualify as scientific – must be proved to be falsifiable, i.e. there must exist conditions of at least one experiment which can demonstrate the theory to be completely false, incompatible with facts. Thus, un-falsifiability or irrefutability of a statement (theory) is not a virtue, as it is often claimed, but a vice. Each genuine test of a theory proves to be an attempt at falsifying or refuting it. Controllability coincides with falsifiability with some theories being controllable or exposed to confutation and others not so much. The latter ones, one might say, run considerable risks.

Figure 1. Location of the Abbey of Santa Maria della Matina, San Marco Argentano, Cosenza, Italy.

The Abbey of Santa Maria della Matina. Three Interpretations from the Large to the Small Scale

One of the nodal points in this research is the definition of model typologies we can construct with systems of massive data acquisition (high or low cost) in relation to the information that the very same models transmit in representation scale fixed at the point of departure. Another fundamental aspect seems to be the comprehension of the quality level of the models based on the diverse methodologies performed as well as their scalability (Alby et al. 2009).

The Abbey of Santa Maria della Matina at San Marco Argentano (Cosenza, Italy) is an ancient complex of buildings founded in AD 1065 as a Benedictine monastery. Later it became the property of the Cistercian order. The preset configuration of buildings corresponds only in part to the original plan. In AD 1652 part of the Abbey was abolished, and the whole was turned into a manor farm. Nowadays it belongs to the state. The particular structure and the

Figure 2. The Abbey of Santa Maria della Matina: a secret piece of Cultural Heritage.

material aspect of the edifice have been found to be amenable to an in-depth study of a series of problems, for example that of metric accuracy and the information that can be drawn from its chromatic data, both of which are fundamental for the cognition and documentation of architectonic heritage on various scales.

By establishing the adequate representation scale during the stage of survey planning, we can critically describe various characteristics of the object under study.

The decision was made to study various subjects in-depth, which were selected from the organization of the architectonic complex in order to evaluate the efficacy of integrated surveying. This included the main façade, which delimits the internal court on urban scale, the chapter hall on the architectonic scale, and a column capital on the detail scale. The research was conducted only on the external surfaces. The surveying operations have been carried out following the project of a unitary survey. However, one of the characteristic features of the artifact is its complex articulation related to the different construction stages in which the edifice was realized as well as to its transformations and the recent restoration of some of its features. Theses peculiarities, apart from

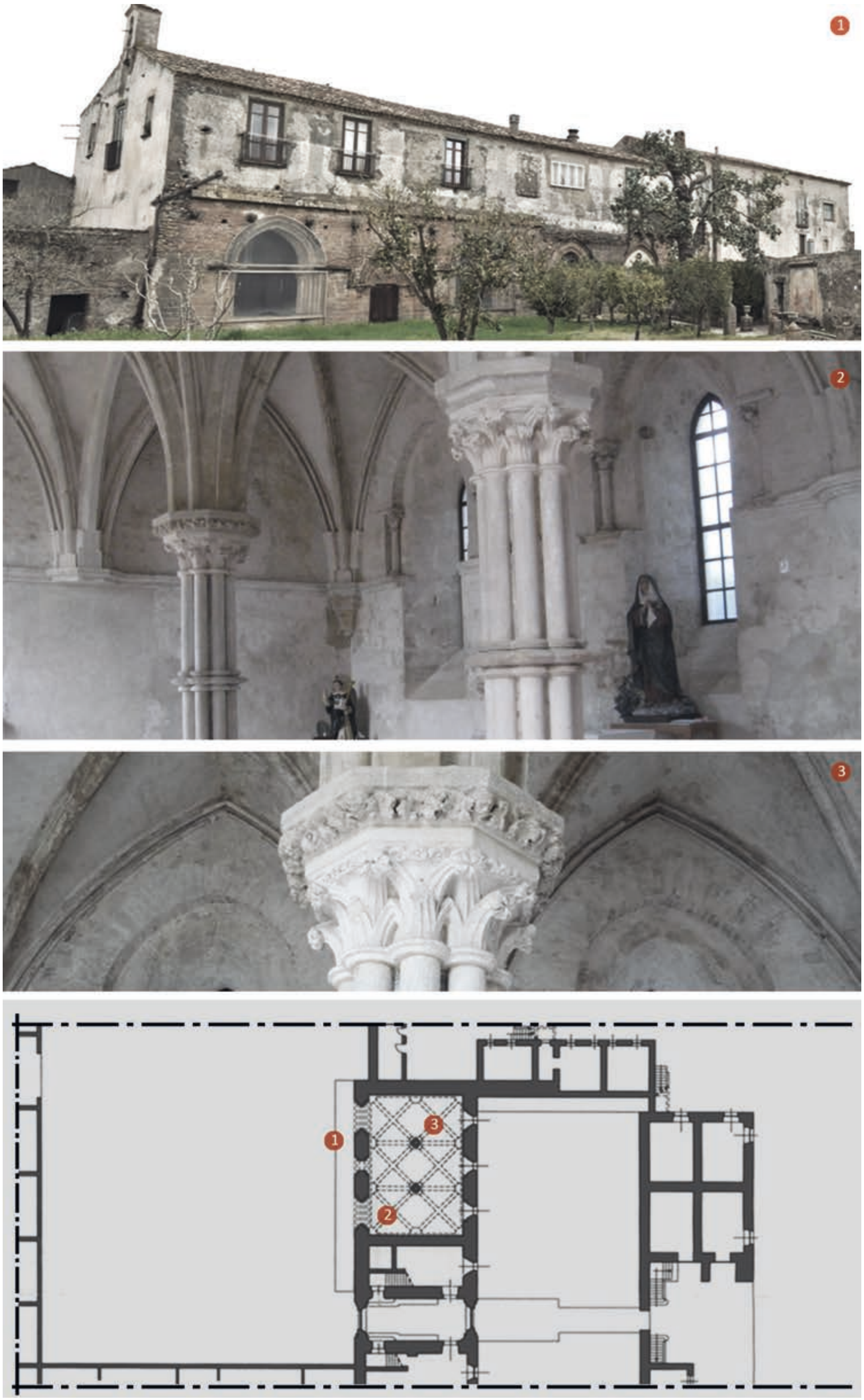

Figure 3. Three case studies on three different scales:
1) urban scale,
2) architectural scale,
3) detail scale.

the adopted aim to represent it on different scales, have yielded concrete premises on the basis of which to work out a project of the survey both general and detailed.

The three case studies were analyzed independently of one another, although a project of placement survey has been executed. During preliminary planning, indispensable for carrying out the survey scientifically as well as for speeding up field activities, problems of a methodological nature were addressed and following the almost well-established practice the decision was taken to integrate various methods and instruments (Baglioni and Inglese 2015; Bianchini 2012; Bianchini, Inglese, & Ippolito 2016). Data acquisition carried out through integrated instrument surveying[4] availed itself of various non-contact surveying methodologies (3D laser scanning, Structure from Motion and Image Matching, photo-rectification) with the goal of obtaining global representation, detail representation, or a specific analysis of material aspects of surfaces (Brown and Lowe 2005). The information acquired have then been organized in order to make sure that the cognitive picture of the object under analysis be as complete as possible. The approach adopted envisages a comparison of data for all case studies obtained in the familiar process of 3D laser scanning with the data provided by expeditious and low-cost methods, like Structure from Motion and Image Matching (SfM/IM). We then compared the metric accuracy and the information derivable from the color data and surfaces, all with the aim to construct models on the 1:50 scale[5]. In fact, we can now assess the metric accuracy of numerical models by managing two parameters: probe and sample spacing[6].

4 A 3D laser scanner Leica Geosystem C10, a Leica total station Geosystem TS02, a photo camera Reflex Nikon D90 with 35mm focal length, a photo camera Reflex Canon 450D with 50mm focal length were the instruments used.

5 Digital representation retrieves the three-dimensional character of the object surveyed. In the realm of the virtual, the graphic model can be represented without being reduced in scale in relation to reality. It can be said, therefore, that also with digital models it is possible to attribute reference to scale in order to identify its capacity to reproduce reality on the basis of the level of detail and the uncertainty possible to achieve (Bianchini 2012).

6 In the project the two main parameters of scanning, that is sample spacing (scanning pitch transformed into a sphere which covers ideally the part to be surveyed) and the probe (the radius of the very same sphere) have been defined in terms of the objective of the survey. Considering that the distance between two successive points has to be approximately compatible with the uncertainty level - controlled on the basis of the scale and the final elaborations to be realized – the sample spacing of 1cm x 1cm and the variable probe between 4.00-8.00 m for internal ambiences and between 8.00 and 20.00 m for external ones have been set up. For some details, like parts of the walling in case of the facade and elements of particular architectonic value as in the case of the chapter hall, scans with the sample spacing of 5 mm x 5 mm or 2 mm x 2 mm have been conducted.

Massive Data Acquistions: High Cost and Low Cost Technologies

A general survey of the whole architectonic complex was the first step in the research conducted. The survey project envisaged the adoption of the open polygonal topography formalized into six stations. It started at the entrance to the edifice and ended in the chapter hall. Topographic measurements enabled us to acquire 50 targets useful for adjusting the system of reference with that of the laser scans as well as for positioning significant points applied to support photographic rectifications. Laser scans were carried out by positioning the instrument at exactly the same points as those of the polygonal topography stations.

The project for the photographic survey of the façade was planned for a long time, the façade being the most complex part of the edifice considering its size, the material stratification, as well as vegetation, which partially covers the edifice, and differences in the altitude profile. All these elements considerably influenced the possibility of distributing the “takings” in a homogeneous way and so, the 64 photographic shots[7] were taken at various distances, in some cases from a point very close to the façade. The process of photographic acquisition was followed by photo elaborations done with Agisoft Photoscan[8]. The model of the façade was realised part by part, seeing that some photos taken from too short a distance from the object invalidated their overall construction.

The definition of the final model with SfM/IM was possible by comparing it with the point cloud obtained with laser scanning. This course of research allowed us to evaluate its precision level (El-Hakim 2006; Goesele et al. 2007). The first registration was carried out by following a manual procedure which imposes the necessity to recognize homologous points in two different clouds.

The model obtained through this procedure,

7 Effected with a Nikon D90 with the focal length of 35 mm and 50 mm.

8 In the course of the research, three other open source software packages, Arc3D, Photosynth, 123D Catch, were compared with Agisoft PhotoScan. Paid software was chosen because of a great number of vertexes/polygons with which it generates meshes in comparison with others, and because of the higher resolution of images that it can handle.

Figure 4. Urban scale, the Façade: numerical model derived from laser scanning, numerical model derived from Structure from Motion and Image Matching, architectural 2D model.

compared by means of open source CloudCompare software with the cloud point acquired by 3D laser scanning, revealed an average deviation of 3.7 cm[9]. Considering the metric quality of acquired points paramount and the uncertainty level linked to their identification in the photographs, we decided to make another registration attempt using 30 targets topographically measured and some points on the façade. The new registration was more accurate that the first one. It yielded 10 million points and was again compared with the numeric model derived from laser scanning. This time the average deviation was 1.6 cm. This was found to be compatible with the results we expected, as far as the metric aspect was concerned, and suitable to 1:50 restitution scale, whereas the first registration could only support the 1:200 scale.

9 The measurement is a set of three data: number, measure unit and uncertainty. The latter can be assessed with proper mathematical procedures. The standard deviation or average error can be referred to as the uncertainty of the measurement. Standard deviation is an index of statistic dispersion, that is, the estimation of datum variation. This is what is often referred to as the measurement error.

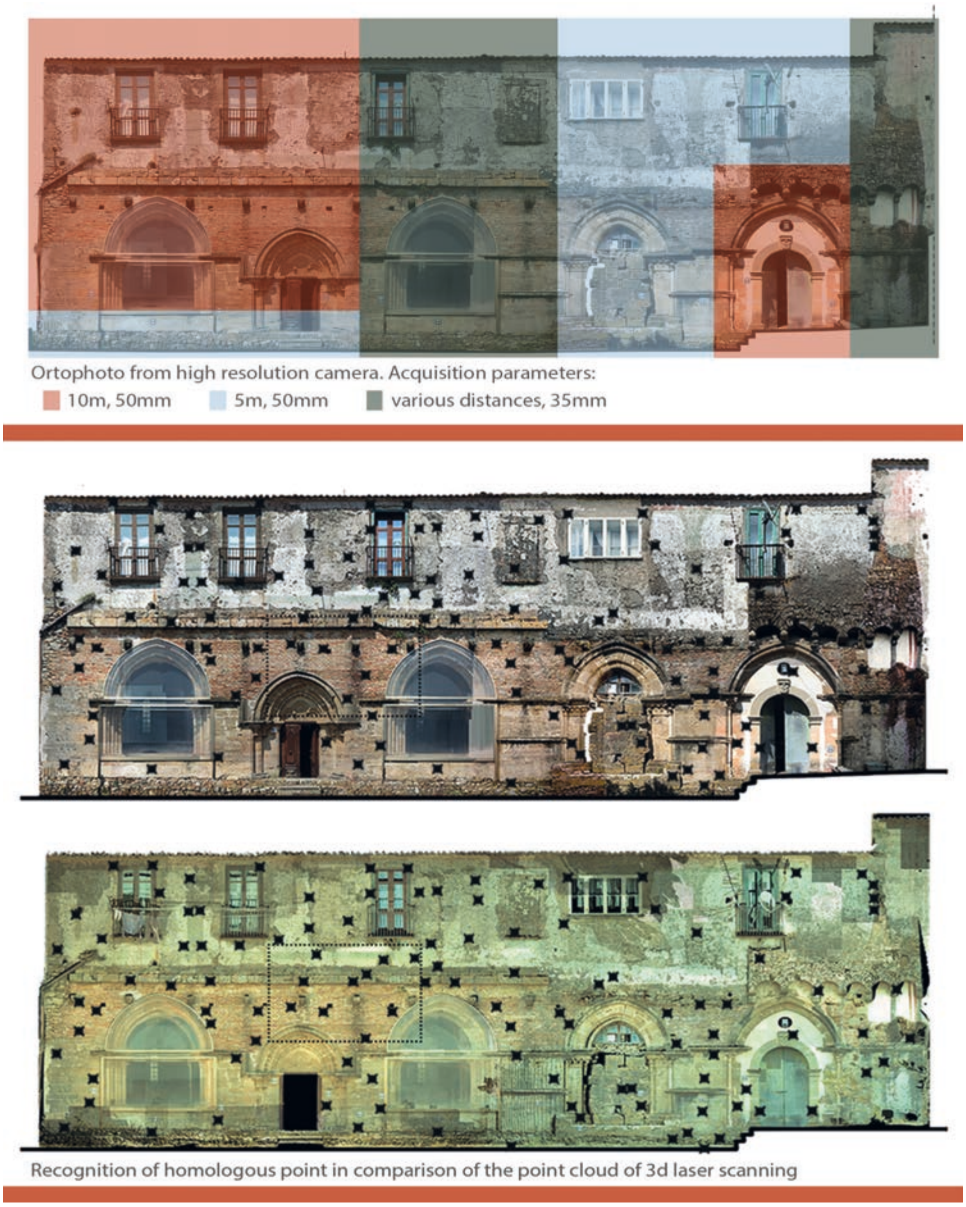

Figure 5. The construction of the orthophoto of the façade derived from high resolution camera.

Also, a photographic campaign had been carried out for the façade[10], photographs having been taken at different distances from the object, in order to obtain images to be rectified by the RDF opensource software, and then, by postproduction operations to construct photo plans. The average scale of the photogram[11] made it possible to construct a 1:100 scale model.

Having obtained the information necessary for representation at a large scale, we applied the same procedure for surveying and representing at an architectonic scale. The procedures adopted for the Chapter Hall confirmed the results obtained earlier, so the optimization of the numeric model obtained after 118 shots[12] and with 32 targets, allowed us to reach the average deviation around 1.7 cm, which made it possible to construct a 1:50 scale model. Also, in this case, the deviation was calculated by comparing the cloud obtained with SfM/IM with the cloud of the laser scanner.

The last case study was at the architectonic scale. It concerned specifically the capital in the Chapter

10 Realized with a Nikon D90 with the focal distance of 35 mm.

11 Mean scale of the photogram: the relation between the dimension of the photogram and the real object dimension represented in it, obtained with the formula 1/s = f/D, in which s = photogram scale, f = focal distance, D = average distance between the object and the camera.

12 Carried out with A Nikon D90 with the focal distance of 35 mm.

Figure 6. Architectural scale, the Chapter House: numerical model derived from laser scanning, numerical model derived from Structure from Motion and Image Matching, architectural 2D model.

Hall. Its model has been constructed on the basis of 26 images[13]. In this context the SfM/IM technique, thanks to the effortless handling of the camera in comparison with the laser scanner, proves to be able to resolve all the limitations generated by shadow zones and undercuts that then produce considerable gaps in the data. Because the average deviation achieved in the last case was 0.14 cm, it was possible to edit the elaborations to the 1:10 scale.

13 Obtained with a Nikon D90 with the focal distance of 50 mm.

Figure 7. Detail scale, the Capital: numerical model derived from laser scanning, numerical model derived from Structure from Motion and Image Matching, architectural 2D model.

The best results, therefore, can be obtained at the medium and small scale, whereas for the large-scale models, integration with other methodologies provided the indispensable control parameter. Hence, clearly, the data extracted with integrated surveying methodologies prove to be not solely comparable, but – considering the error deviation achieved – help structure out a heterogeneous database of information that can describe the object analyzed more completely..

Datum Color: Instrument of Knowledge

Having demonstrated that cognition of architecture at any scale does not end with identifying its geometric and morphological characteristics but has to be based on a selective and specialized reading of various aspects, we proceeded with an analysis of the object taking advantage of additional data acquired earlier. Another type of comparison we wanted to experiment with was that obtained from the interpretation of the RGB datum acquired with different surveying methods (laser scanning, SfM/IM, and digital photograph accurately rectified), which help towards the chromatic and material cognition and reading of surfaces and of the state of their preservation.

The case studies demonstrate that the resolution of the texture of the mesh model obtained with SfM/IM is superior to that acquired from images provided by a laser scanner for visualizing the point cloud with the RGB mode. This feature makes the model derived from SfM/IM more adequate, with respect to the scale initially adopted as the objective to be attained, to document with more reliability and coherence the state of the object as well as the changes it was subject to.

However, acquisition with the laser scanner also makes it possible to visualize the RGB data in reflectance mode[14].

A comparison of the data acquired with various techniques of massive acquisition show that this very datum inspires interesting considerations on the preservation state of surfaces. Reflectance constitutes a parameter which operates on the extension of the scale of chromatic values and thus enables us to better assess material discontinuities, degradation phenomena, traces of old coloring and information not easily deducible. Therefore, visualizing views in parallel projection of the numeric model in the RGB mode of reflectance at a specific interval of values, it is possible to glean, on the basis of various visible colors, information that is not immediately perceptible to the naked eye on the texture and layers of the artifact under study. Relocation of chromatic values in various ranges (in this concrete study the interval of values that made for a better visualization of phenomena was identified to be between 0.18 and 0.48, dividing continuously the field into four bands of further limited values) made it possible to read specialist aspects like the plastering, mortars, mural parameters and their coloring as well as the state of degradation, identifying old and recent parts, like, for example, doors installed at different time periods.

14 Reflectance indicates the proportion of light striking a surface which is reflected off it. This value has a physical significance linked to the characteristics of the material of which the surface struck by a laser is made.

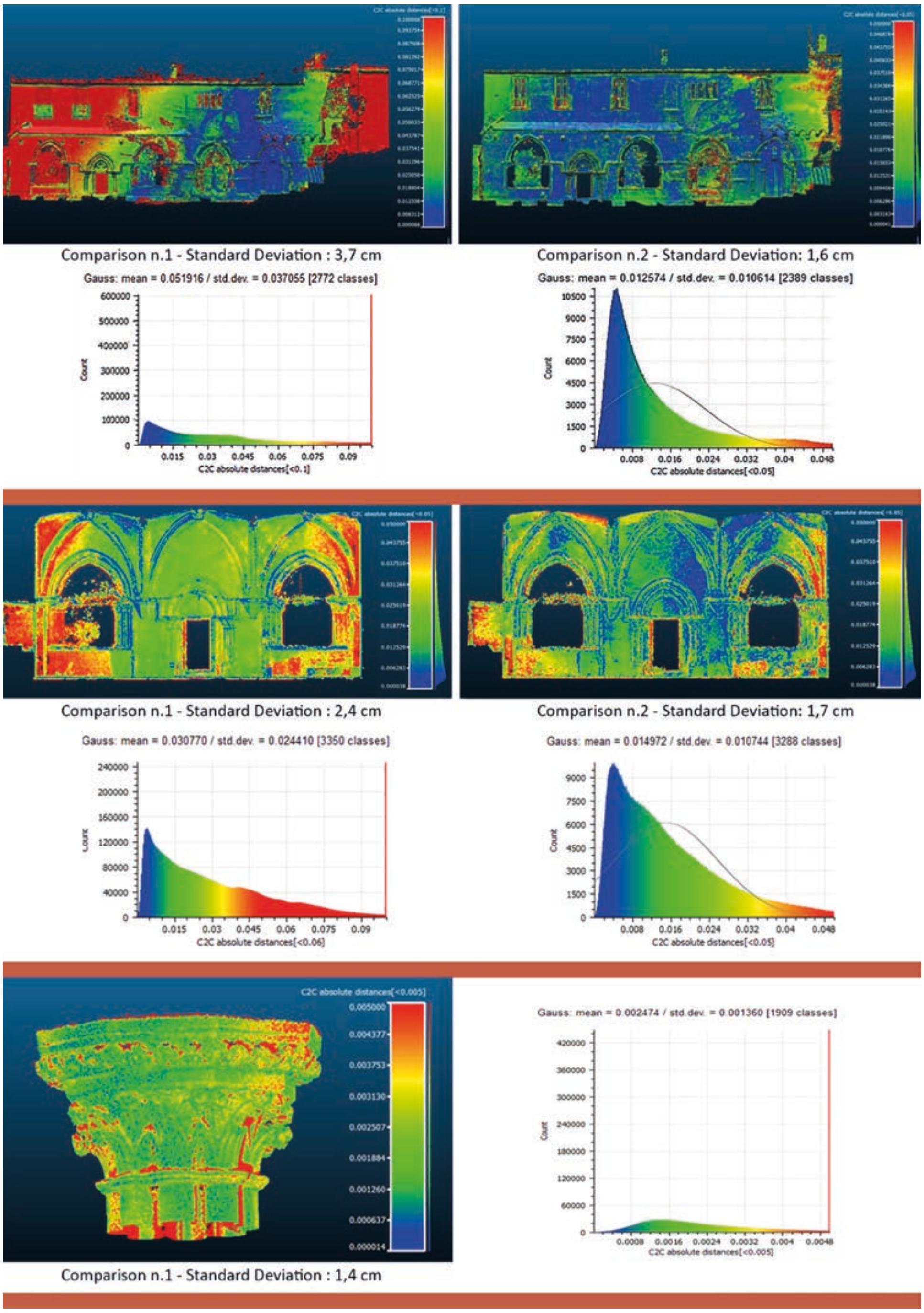

Figure 8. Comparison between numerical models derived from laser scanning and Structure from Motion and Image Matching, with software CloudCompare, for the three cases studies, and evidence of their deviation graphics.

Conclusions: Beyond the Digital

The integration of massive acquisition instruments, re-formulating the traditional process of defining classical 2D elaborations, integration of digital representation techniques, the possibility to communicate through innovative output, they all have provided the basis for investigating all the material and non-material aspects fundamental for understanding the architectonic complex analyzed. The present study made it possible to clarify certain problems connected with the possibilities to compare and superimpose a series of information on reality by applying multiple surveying methodologies. It has again demonstrated the efficiency of the integrated approach. Availing ourselves of a series of thematic models and the analysis of constitutive elements of the objects under study derived from various reading modes, we were able to arrive at a clear understanding of the significations that the attentive surveyor has to be able to grasp and communicate, all the time having in mind the critical stance towards the whole process.

Figure 9. Orthophoto of the façade obtained through three different methodologies: High Resolution camera, Structure from Motion and Image Matching, Laser scanning-RGB mode. Comparison about RGB data.

The comparison of models reveals that the two methodologies, mainly used nowadays, the laser scanner (high cost) and the SfM/IM (low cost), yield results different for the urban, architectonic and detailed scales. In general terms, the advantage of the low-cost methodology is the speed of acquisition together with the fact that it is easy to use and to transport, economic, and that it ensures the repeatability of the whole process. However, the acquisition procedures are still strictly dependent on the nature of the object analyzed and the context in which it is set. The best results have been obtained in the case study at architectonic scale and that of the detail. As concerns the large scale, we have not been able to liberate the process from other integrated methodologies to guarantee proper metric accuracy.

It is almost obvious now that the massive acquisition technologies have to be integrated according to the potentialities inherent in each of them, the objective being to construct heterogeneous models exhaustive in all their aspects. Moreover, it becomes indispensable at the historical period when the use of massive acquisition instruments and digital representation are already a language spoken and accepted, that the researcher be able to grasp not only the canonical applications, but also the potentialities of the means at his disposal to use them to his advantage in a critical and alternative manner in order to reach the highest level of cognition of the artifact. The importance of two fundamental aspects which open and close the whole process seem to become apparent: the survey design and data archiving. Hence planning activities to be carried out and choosing instruments adjusted to the scale of models to be studied prove to be fundamental. Equally indispensable in the digital epoch is the correct administration of

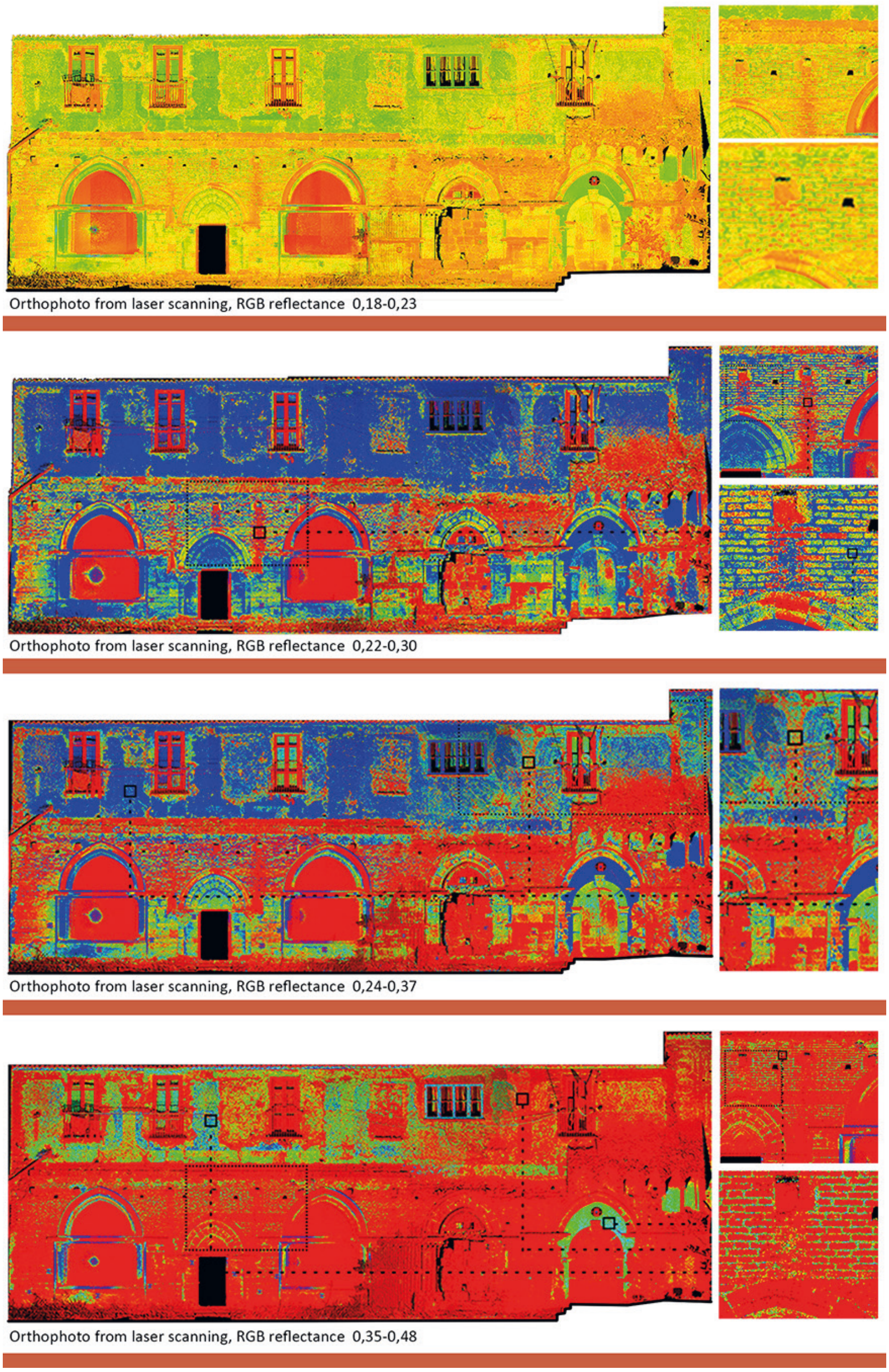

Figure 10. Orthophoto of the Façade obtained through laser scanning-reflectance mode, into 4 different extensions of the chromatic scale of values.

the data obtained both before their acquisition and after their elaboration, including the factors of sharing and implementation. Models constructed on the basis of various assumed objectives will become an integral part of the database which will allow us to achieve what we aspire to: a really profound knowledge of the artifacts we wish to preserve and communicate.

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Analytical Comparison of Optical Methods to Evaluate the Potential of the Photo Modelling Technique for Cultural Heritage

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Abstract

A comparison of commercial 3D photo modelling software applications is presented. Starting from the simple acquisition of digital images, and based on the principles of photogrammetry, photo modelling represents a user-friendly and economical way to digitally preserve and three-dimensionally reproduce cultural heritage objects. The aim of this research is to evaluate the potential offered by the technique by reviewing a range of commercial and opensource software applications and making a comparison with reference data points obtained from a structured light 3D scanner. A marble artefact was selected from the collection of the Galleria Nazionale dell'Umbria di Perugia (Italy) as a test case for the analytical comparison of these two optical techniques.

Keywords: photo modelling, 3D modelling, cultural heritage, survey, measurement criteria

Introduction: Photo Modelling

Due to the recent development of computer graphics technologies along with an increasingly competitive demand for hardware and software solutions, the optical acquisition of three-dimensional data represents an innovative tool compared to more traditional techniques. Based on the use of a simple digital camera, photo modelling (Buscemi et al. 2014; Filippucci 2010) is an optical technique based on the principles of photogrammetry, which is able to yield results comparable to those of commercial optical instruments, such as structured light 3D scanners.

This technique is accessible to a wide range of users because of the low-cost nature of the instruments involved. Digital cameras take the place of expensive machines, instruments, and devices, and opensource software and freeware are widely available along with commercial solutions.

Photo modelling integrates survey, 3D modelling, and representation (De Luca 2011), giving the possibility to obtain highly detailed three-dimensional surveys in fields such as cultural heritage. As a conservation tool and developer of cultural information, the use of this technique is helping to promote virtual tourism in museums and is employed for teaching purposes and for restoration (De Luca 2009).

The reconstruction of 3D models starts from a preliminary analysis of the environmental conditions (i.e. environmental light) and the object to be measured. The first step involves the acquisition of several images with a common digital camera, with those images containing spatial information of the object to be measured. The result strictly depends on the acquisition plan and on the quality of the images. For this reason, the light of the surrounding scene must be as uniform and homogenous as possible. As well, the object must be accessible from different angles in its entirety (Figure 1).

The reconstruction steps are the following:

a. image acquisition
b. image processing
c. point cloud reconstruction (sparse cloud and dense cloud)
d. 3D model reconstruction (triangular mesh shown in Figure 2)
e. editing, texturing and visualisation.

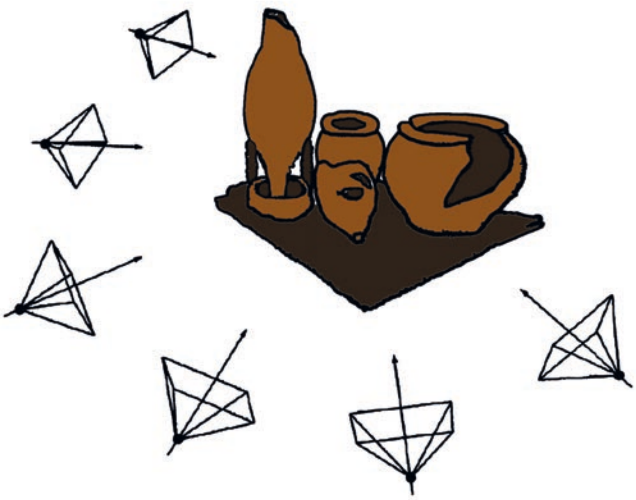


Figure 1. Image acquisition planning: ideally the pictures need to be taken moving around the vertical axis of the object at 360° for isolated objects and 180° for flat ones, with the camera oriented in the range of 30° / 45°.

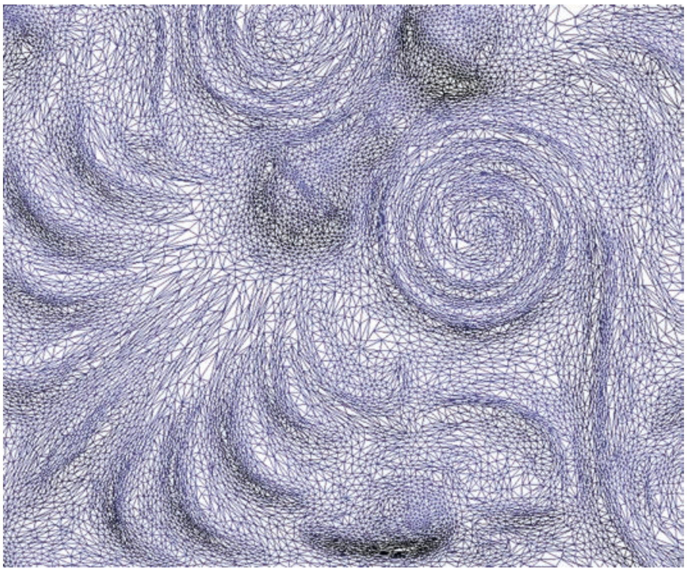


Figure 2. Triangular mesh reconstruction.

The Structure-from-Motion (SfM) algorithm (Szeliski 2010) is the main principle of the image processing step (b): the algorithm processes the images and automatically matches the common key points of a series of pictures, identifying a set of sparse correspondences and the positions of the cameras. After the extraction of significant points (common to three or more pictures), the algorithm obtains photographic parameters and matches the homologous points in multiple images, finding the spatial 3D coordinates of each point. A *sparse reconstruction* algorithm obtains the real coordinates in *x*, *y* and *z* for each key point, materialising them in a scattered point cloud (c), a cloud of low-density points. A *dense-matching* algorithm increases the number of points in the sparse cloud, giving as output a dense point cloud (Figure 3).

Test Case and Experimental Set-Up

The experimental set-up is based on a comparison between a commercial structured light 3D scanner (Creaform GO!Scan50) and a DSLR camera (Canon PowerShot SX30 IS) for photo modelling reconstruction (Figure 4), combined with several point cloud processing software solutions. The Creaform Go!Scan50 is a structured light 3D scanner (LED white light) with a large field of view (scanning area, 380 × 380 mm). The accuracy goes up to 0.100 mm and the resolution, 0.500 mm. As a test case, the selected artefact is an italic marble lion's head, "Doccione di fontana" of mid XIII century, from the collection of Galleria Nazionale dell'Umbria di Perugia, Italy (Figure 4).

SfM Photogrammetry Software Solutions

As a preliminary evaluation of the potential of photo modelling, a range of 3D point cloud processing software applications are classified by data processing time, difficulty of usage, and cost, and are subdivided into 3D web-service, open-source software, and commercial solutions (Figure 5).

Agisoft PhotoScan and Photomodeler Scanner are advanced and detailed commercial software applications based on photogrammetry principles. Visual SfM toolkit, based on the SfM technique, gives outputs comparable to those of a 3D laser scanner. Arc3D is a freeware tool and allows users to upload images to an online web server and receive a full three-dimensional scene. Autodesk Remake (low cost) and Autodesk 123D Catch (freeware) enable

Figure 3. The sparse reconstruction algorithm transforms the x, y and z coordinates of common key-points in a scattered point cloud (left). The dense-matching algorithm increases the amount of data key-points giving as result a dense point cloud (right). Artefact selected in the collection of the Archaeological Museum of Amelia, Italy.

Figure 4. Structured light 3D scanner Creaform GO!Scan50 (left) and DSLR camera Canon PowerShot SX30 IS (centre). Test case: italic marble lion's head, "Doccione di fontana" (right), Galleria Nazionale dell'Umbria di Perugia, Italy.

Agisoft Photoscan

Time data processing	average
Difficulty	average
Cost	160€ ca.

Arc3D

Time data processing	fast
Difficulty	very easy
Costo	free

PhotoModeler Scanner

Time data processing	slow
Difficulty	difficult
Cost	2240€ ca.

Autodesk ReMake

Time data processing	average
Difficulty	easy
Cost	396,50€ / year

Visual SfM

Time data processing	average
Difficulty	average
Cost	free

Autodesk 123D Catch

Time data processing	fast
Difficulty	very easy
Cost	free

Figure 5. 3D point cloud processing software: Agisoft PhotoScan, Visual SfM, Arc 3D, Autodesk ReMake, Autodesk 123D Catch and Photomodeler Scanner.

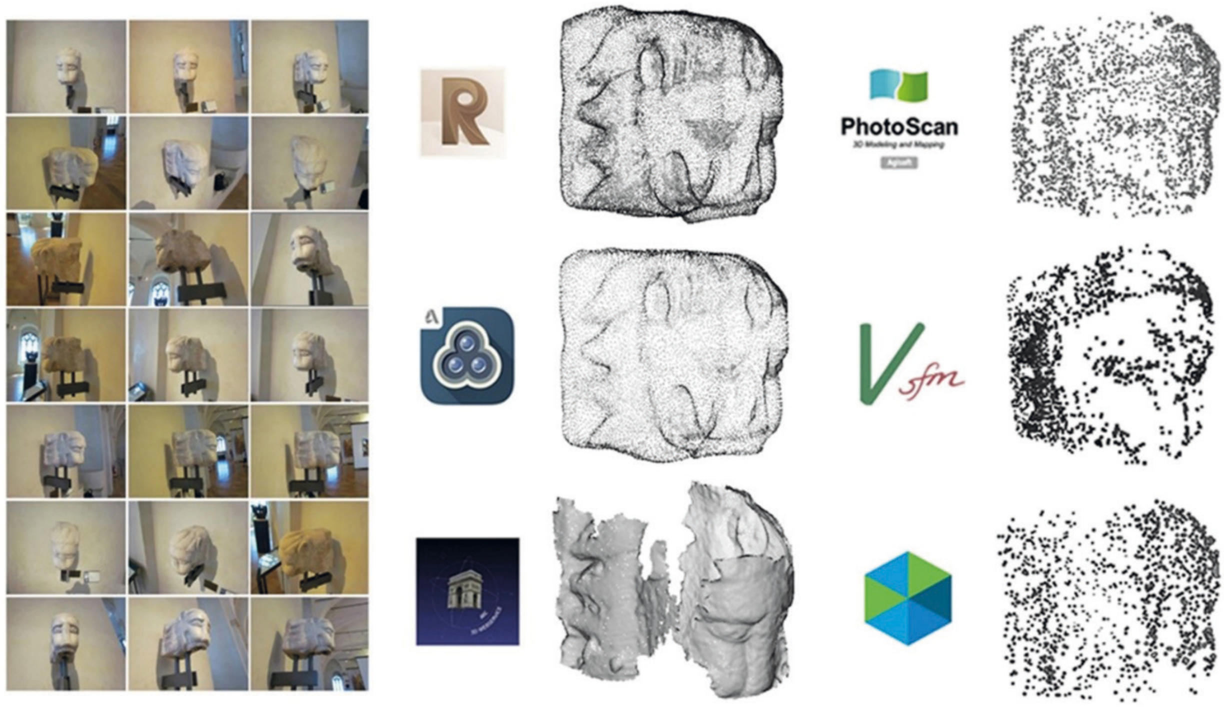


Figure 6. Images acquisition and data processing: test point clouds processed and filtered with the selected software solutions.

Figure 7. Heat map of the comparison between reference polygonal model and test point cloud: cross section visualisation (left) and distributed colour map of the computed deviations (right).

the user to achieve rapid and automatically acceptable results with a good level of detail.

The 3D point cloud processing procedure begins with the navigation and filtering (i.e., cleaning, noise removal, outlier removal) of the data points acquired (Bianchini 2008). Once the point cloud is satisfactorily edited, it can be converted into a polygonal model (triangular mesh). The meshing starts from the input of data vertices, then edges and faces are generated. The result obtained is a set of vertex coordinates converted into a polygonal surface (Russo et al. 2011).

Data Processing and Results

A "measure" is a range of values, acquired with the purpose of controlling a process, performing the calibration of an instrument or allowing the physical understanding of a partially known phenomenon (Rossi 2010). Referring to this assertion, the reliability of the photo modelling technique is tested by considering the graphic representations of 3D and 2D metric comparisons between the test point clouds (Figure 6) and the reference .stl polygonal model from the structured light scanner.

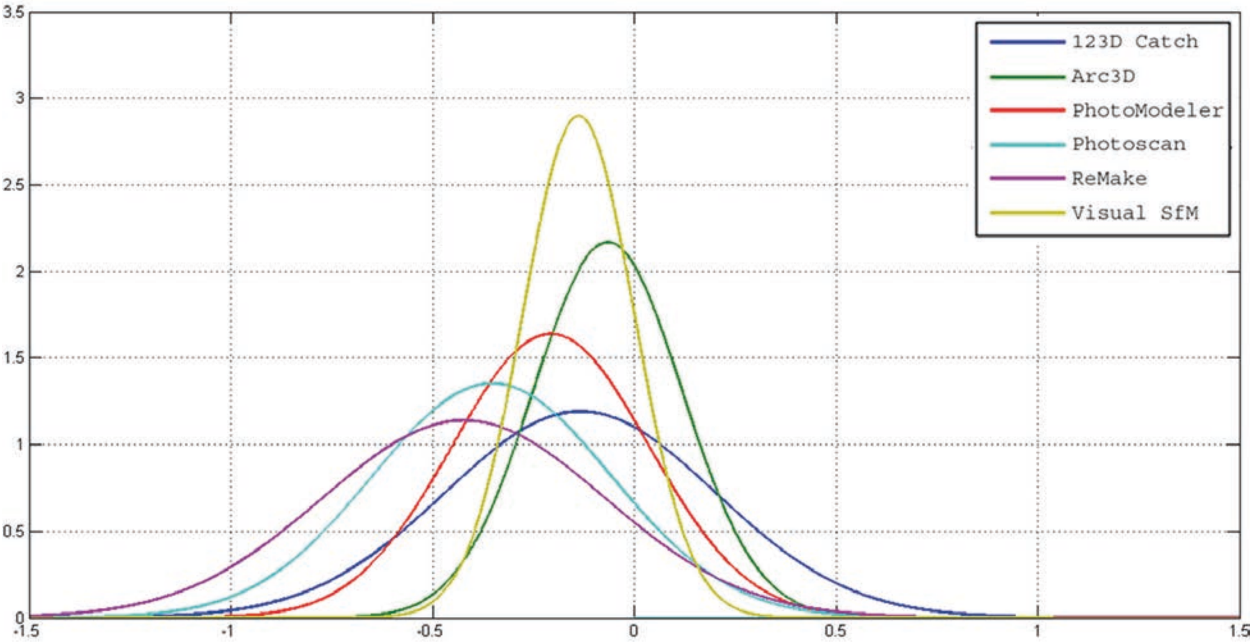
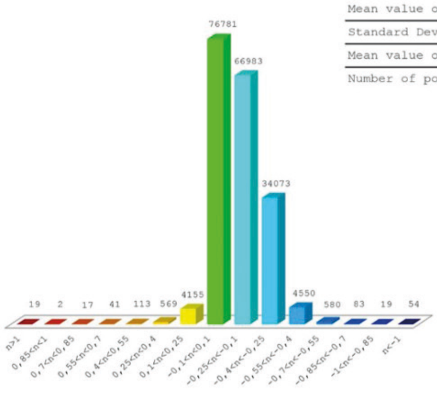


Figure 8. Probability density diagram.

Visual SfM

Standard Deviation distribution	Number of point
n>1	19
0.85<n<1	2
0.7<n<0.85	17
0.55<n<0.7	41
0.4<n<0.55	113
0.25<n<0.4	569
0.1<n<0.25	4155
-0.1<n<0.1	76781
-0.25<n<-0.1	66983
-0.4<n<-0.25	34073
-0.55<n<-0.4	4550
-0.7<n<-0.55	580
-0.85<n<-0.7	83
-1<n<-0.85	19
n<-1	54



Mean value of distance between models	-0.13778 cm
Standard Deviation	0.13766 cm
Mean value of all differences +- devstd	-0.00011882 cm, -0.27544 cm
Number of points	188039

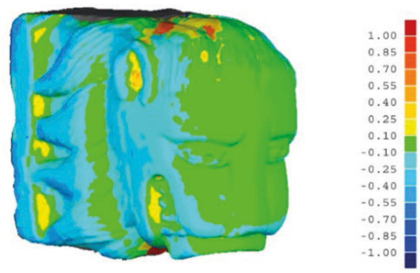


Figure 9. Comparison with reference model and results (Visual SfM): a considerable amount of surface presents deviations within the range of -0.25 and +0.1 cm.

Agisoft Photoscan

Accuracy	low
Precision	average

Arc3D

Accuracy	high
Precision	average

PhotoModeler Scanner

Accuracy	low
Precision	average

Autodesk ReMake

Accuracy	average
Precision	average

Visual SfM

Accuracy	high
Precision	high

Autodesk 123D Catch

Accuracy	low
Precision	low

Figure 10. Results summary: accuracy and precision of the results obtained after the comparison between photo modelling technique and structured light 3D scanner.

The alignment for the comparison is made at first manually, identifying point pair correspondences between source and reference objects. After the manual pre-alignment, a Best-Fit Data to Reference model algorithm is used to match the source point cloud with the reference .stl within a maximum distance of 0.1 cm. After the alignment is completed, the analytical comparison is executed using a commercial metrology inspection tool. In order to assess which data points are considered as outliers, a range of 15 intervals of acceptability is set (between ±1.0 cm deviations).

The heat map of the deviations is distributed on the point cloud, rendered with a customised colour map (Figure 7). From the comparisons obtained, it is possible to export a matrix in .csv format of the spatial coordinates (x, y, and z) of the data points (each point of the test cloud and its correspondent nearest neighbour on the reference surface) and the values of the mutual distances for each pair of data points. The results of the probability density distributions of the test point clouds processed with the selected software solutions are shown in Figure 8. The best results are given by the comparison between the reference .stl and the point cloud processed with Visual SfM toolkit (Figure 9).

Conclusions

In this work the potential of the innovative and low-cost photo modelling technique was presented. The experimental tests show that the results achieved are comparable to the outputs given by commercial instruments, such as a structured light 3D scanner. Additionally, the use of freeware point cloud processing software solutions is a bonus given the affordability of this technique for any type of user. Based on the comparison of results, the Visual SfM toolkit represents a good compromise between accuracy and precision (Figure 10).

One of the important applications of this technique is the possibility to preserve the historical memory of Cultural Heritage objects, allowing for the reproduction of damaged artefacts, as well as the development of virtual catalogues of museum collections, with the aim to consider three-dimensional models as a reference for restorations. With the recent development 3D printing, photo modelling easily allows for the duplication printed versions of any artefact to temporarily or permanently replace objects damaged or degraded. In conclusion, photo modelling is an efficient technique, able to economically preserve historical and cultural heritage and guarantee restorative measurement authenticity.

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Batten Down the Hatches! Digitizing and Displaying Finds from the Spanish Plate Fleet Wrecks

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Abstract

Artefacts from the Spanish Plate Fleet Wrecks of 1715 and 1733 provide an unmatched archaeological window into 18th century life. To publicize these important finds that are often overshadowed by the wrecks' alluring gold and silver treasures, the Florida Bureau of Archaeological Research Collections and Conservation section created an online 3D museum of selected artefacts. This presents our experiences as we plunged headfirst into the world of 3D photogrammetry and online museum development. We highlight our successes and failures with photogrammetry techniques, model creation, general workflow, and 3D web design for education and public outreach.

Keywords: photogrammetry, public outreach, web development

Out of Port: Starting an Online 3D Museum

The Florida Bureau of Archaeological Research (FLBAR) Collections and Conservation section is responsible for curating and conserving artefacts recovered from Florida state-owned and state-managed lands and waterways. FLBAR's facilities are located in Tallahassee, where they currently house millions of artefacts that have been collected since the 1970s. These artefacts are held for the benefit of the people; therefore, the facilities are made accessible for researchers and loans of objects are regularly granted to museums, institutions, and historical societies across the country. Given the volume of materials, the limited staffing, and the facility's inherently fixed location, increasing public access to and awareness of the collection is, nonetheless, challenging. As one way to address this challenge, in 2016, FLBAR Collections and Conservation staff decided to experiment with the creation of a limited, online 3D museum, which could be expanded upon in the future.

The 3D modelling and dissemination of cultural heritage materials has a rich history (Forte and Siliotti 1997; Niccolucci 2007; Pescarin et al. 2012; Reilly 1990, 1992), and researchers have employed various techniques to produce their models, including laser scanning, structured light scanning, and photographic techniques (Hindmarch 2015: 35–59). Over the last decade, successful outcomes of these approaches have included the Virtual Museum of Iraq[1] (Chiodi 2007), Smithsonian X 3D[2] (Terdiman 2012), and the 3D Petrie Museum[3] (Hess and Robson 2015). Certainly, in our attempts to build a 3D presence online, we were not the first, but nonetheless, as newcomers to the process, we had difficulty finding a ready-made method for our objects, although general information on establishing workflows exists (e.g., Pfarr-Harfst 2016: 43).

Following current museum and cultural trends (Milroy and Rozefelds 2015), the FLBAR's major goals in designing an online 3D museum were to improve public outreach; to display fragile, rare, or understudied objects; to increase awareness of the

1 http://www.virtualmuseumiraq.cnr.it/homeENG.htm, accessed 26 February 2018.

2 https://3d.si.edu, accessed 26 February 2018.

3 http://www.ucl.ac.uk/3dpetriemuseum, accessed 26 February 2018.

Bureau of Archaeological Research's role in archaeological curation and conservation; and to counter the mistaken perception that we hide artefacts. To reach these goals, we decided to employ photogrammetry to model small- to medium-sized objects and to build a custom, scalable website, with which to display these models in a manner accessible to both mobile and desktop users. The Bureau's millions of artefacts offered a cornucopia from which to choose an exhibit theme. Ultimately, we elected to digitize and display a select group of objects from the Spanish Plate Fleet Wrecks.

Favourable Winds: Choosing Artefacts from the Spanish Plate Fleet Wrecks

The Spanish Plate Fleet, so named after the Spanish *plata* ("silver"), which it carried in abundance (Craig 2000), was a convoy system that existed between the 16th and 18th centuries. In order to carry the vast resources extracted from the New World, a formalized arrangement of armed ships and cargo ships travelled along fixed routes. In actuality, there was not one, but two fleets, each of which was tasked with collecting goods from a particular area in the New World; the *Flota* collected goods from Mexico and the *Tierra Firme* collected goods from South America. After rendezvousing in Havana, the two fleets sailed as one to Spain, where they would unload their cargo. The Plate Fleet's return to Spain was fraught with dangers precipitated by the limitations of contemporary sea maps and marauding pirates. During the summer sailing season, their route, too, was treacherous. After leaving Havana harbour and before turning to cross the Atlantic, the convoy sailed along the Florida Keys and then hugged the east coast of Florida's mainland, that is to say, its voyage led it directly through Hurricane Alley.

Over the centuries, hurricanes took their toll, with major disasters striking the Plate Fleet in 1622, 1715, and 1733 (Fine 2006). Perhaps the most famous wreck from these disasters is the 1622 Nuestra Señora de Atocha, salvaged by Mel Fisher. It is, however, only from the wrecks of the 1715 and 1733 Plate Fleets that the Florida Bureau of Archaeological Research holds large archaeological collections . The choice to build a digital exhibit around these wrecks to the exclusion of the many other well-rounded archaeological collections that are held by FLBAR was made largely because this collection and its history of recovery accorded so well with the project's overarching goals.

Unlike most of the artefacts held by FLBAR, which originate from professional, documented archaeological projects that follow a rigorous permitting process, the artefacts from the 1715 and 1733 wrecks have been and continue to be acquired via an arrangement between treasure salvors and the State of Florida[4]. Of the artefacts torn from the wrecks by these salvors, 20 percent are required to enter FLBAR's collection for the benefit of the people and the preservation of Florida's history. This 80/20 division inevitably results in yearly legal wrangling, in which the salvors attempt to maximize profits while FLBAR attempts to preserve the wrecks' unique archaeological history. As one might also expect, the salvors do not document their finds in any archaeologically meaningful way so that those objects accessioned into FLBAR's collection lack provenience other than the general shipwreck from which they may have been recovered. In effect, the collection of the Plate Fleet Wrecks has arisen from an ill-formed partnership between treasure hunters and archaeologists that presently exists only because of past historical and legal arrangements.

Treasure hunting, the destruction of archaeological sites, and the detrimental loss of our shared human past is now an increasingly visible problem in Florida (James 2017, Springer 2013). The depth of this problem and the ongoing fight between scholarly archaeologists and looters has even touched the Florida Legislature, where proposals were made in 2016 to institute a citizen's archaeology permit; for the meagre fee of $100, any citizen would be allowed to dig up riverine sites for artefacts (Brotemarkle 2016). On the other hand, an archaeologist would still need to follow the rigorous permitting process. To date, this legislation has not been successful thanks to the dedicated efforts of many professional archaeologists and citizen activists, but the future of similar proposals is unknown.

Objects from the 1715 and 1733 Plate Fleets were, therefore, an ideal group for digitization and display. With artefacts from the Plate Fleets, FLBAR

4 This arrangement is governed by Florida Administrative Code 1A-31.

Figure 1. The route of the Spanish Plate Fleet, including the separate routes of the *Flota* and *Tierra Firme*, in the New World. The two fleets met in Havana before returning together to Spain.

would expose a set of understudied objects that are frequently overshadowed by the salvors' quest for gold and silver cargo (Burgess and Clausen 1976); would increase awareness of FLBAR's role in preserving Florida history rather than commercializing it. This project would also show that proper curation of these objects is a benefit to the people and would expand the public's awareness that even mundane artefacts provide rich historical information and that such information derives strongly from an object's documented archaeological context, which can be destroyed when sites are overly commercialized, whether legally or illegally.

Of the thousands of possible artefacts from the wrecks, we chose ones that would speak to 18th century human experiences and that would purposefully move the dominant narrative of the Plate Fleet Wrecks away from their gold and silver cargoes and into a more archaeologically meaningful domain[5]. From an initially large set of viable choices, 18 artefacts were selected for final modelling and display online[6]. This number was thought to provide a manageable starting point and the chosen 18 fell neatly into three exhibit groups: weaponry, trade, and daily life. In addition, the artefacts offered a plethora of sizes, shapes, colours, textures, and reflectivity, upon which to hone our photogrammetry skills. For example, the selected grenade was a matte, cracked, lumpy sphere; one of the sanctus bells was shiny, holed, and concave; and the majolica plate was thin, brightly coloured, and had highly detailed paint texture (Figure 2). The immediate challenge was to develop a streamlined photogrammetry process that would generally produce high-quality models in rapid time while also permitting procedural variations to account for the disparate physical characteristics of each object.

Storms on the Horizon: Perfecting the Photogrammetry Process

The process of photogrammetry is simple on paper, but difficult in practice. Despite a long history of use in archaeology and cultural heritage, there is no single standard for how one should employ photogrammetry to model artefacts. As Santos et al. (2014: 1–2) point out, the important institutional factors governing the photogrammetric process are often reducing time and cost, increasing ease-of-application, and establishing a workflow that suits the material being modelled. The final use of the models and their intended method of distribution impact the process,

5 This is not to say that gold and silver coinage are not archaeologically meaningful, only that the wrecks should not be viewed solely as a source for private gain, but also as a fount of archaeological data.

6 A selection of the Plate Fleet models created by the author are available on https://sketchfab.com/charper for viewing or downloading.

Year	Wreck of Origin	Artifact Type	FLBAR #
1715	Cabin Wreck	Metate	93.671.176.1
1715	Cabin Wreck	Nuestra Señora Sanctus Bell	95.50.15870.1
1715	Corrigan's Wreck	Cannister Shot	93.641.166.1
1715	Corrigan's Wreck	Clay Roundel with Lion	94.22.8914.1
1715	Corrigan's Wreck	Jangxi Jar Neck	93.641.163.1
1715	Corrigan's Wreck	San Joseph Sanctus Bell	16.3.77228.1
1715	Douglass Beach Wreck	Abó Polychrome Majolica Plate	93.673.105.1
1715	Douglass Beach Wreck	Gunner's Bar	93.673.89.1
1715	Douglass Beach Wreck	Pewter Goblet	82.170.8359.1
1715	Douglass Beach Wreck	Sword Hilt Cast and Concretion	93.674.35.1
1715	Rio Mar Wreck	Olive Jar	72.18.326.2
1715	Unknown	Silver Sword Hilt	94.36.808.1
1733	Capitana Wreck	Barshot	93.616.54.2
1733	El Lerri Wreck	Adorned Storage Jar	75.8.390.2
1733	El Lerri Wreck	Grenade with Fuse	75.8.472.2 / 75.8.361.1
1733	San José Wreck	Helmsman's Slate	93.605.22.1
1733	San José Wreck	Majolica Escudilla	93.605.265.1
1733	San José Wreck	Spyglass	93.605.1751.1

Table 1. The 18 artefacts from the 1715 and 1733 Spanish Plate Fleet Wrecks that were digitized and included for display on the web.

Figure 2. Objects with varying physical characteristics were selected for modelling, including this brass sanctus bell (FLBAR #95.50.15870.1), iron grenade with wooden fuse plug (FLBAR #75.8.472.2 and #75.8.361.1), and polychrome earthenware plate (FLBAR #93.673.105.1).

too. Models meant for direct research cannot follow the same procedures used to create general educational models (Pfarr-Harfst 2016: 43); whereas the former must provide accurate measurements, the latter must only represent the object holistically without the need to be so exacting in their level of detail.

Since our primary goal was outreach and public awareness, we were spared the issues of producing research-quality models; however, the development of our process was not without problems. Particularly, the diversity of materials, their varying conditions of preservation, and their different scales created many headaches, nor are these issues unique to our collection. These are recurrent problems that one must overcome when modelling an archaeological or cultural collection (Santos et al. 2014: 4–5). It was only over time and through experimentation that we developed a general procedure that permitted the modelling of artefacts of many different materials, sizes, and conditions. At first, though, our failures were many.

Objects that had clear, crisp photographs produced oddly shaped meshes or poor textures. Reflective artefacts especially caused difficulty, and there was a struggle to arrange our lighting in a manner that would make such models work. One particular-

Figure 3. One attempt at a porcelain cup produced a pockmarked, interior-free model due to the impact of surface reflection on the modelling process.

Figure 4. An early try at modelling a gunner's bar resulted in two mismatched halves.

ly egregious failure was a porcelain cup, the surface of which came out pockmarked and the interior of which never materialized due to light reflection (Figure 3). Effectively, modelling artefacts that are reflective or transparent is a major problem in the field, and one that equally impacts laser and structured light scanning (Barsanti and Guidi 2013: 151; Hindmarch 2015: 60–67). Occasionally, the early stages of modelling worked, but in later stages, separately modelled portions of an artefact did not match together correctly and odd pieces were left jutting out into space or overlapping one another (Figure 4). This was typical of monotone artefacts, where Agisoft was unable to determine overlap between photos, and very small objects, where lens distortion may have played a role.

Over time, a general procedure was developed that eased the production of models and in many cases, produced strong results. Still, aspects of the procedure, particularly the intensity and position of lighting, were not based on any fixed method, but were derived ad-hoc from past experience and a familiarity with each object's nuances and peculiarities. The particular rig that we used was built with equipment that FLBAR already owned and was supplemented when necessary with small purchases that fit within the Bureau's limited budget. The rig consisted of a:

1) Canon Rebel T3i 18.0 MP DSLR,
2) EF 50 mm f/2.5 compact-macro lens
3) Altura external flash with diffuser
4) Two compact fluorescent lights
5) Square light tent

We found that the 18.0 MP canon created excellent models, although a lower resolution camera, or even a phone-camera, are sufficient for creating basic educational models. If possible, though, the camera should at least allow manual setting of parameters such as focal length and exposure time (Linder 2016: 5–6). The use of the 50 mm lens, which offers minimal distortion, was ideal for photographing the objects in our facility, but the context of shooting does impact lens choice, and researchers have found success with other lenses (Barsanti and Guidi 2013: 152; Guidi et al. 2015: 341; Kaufmann et al. 2015: 224; Marziali and Dionisio 2017). The choice of flash, lighting, and light tent, on the other hand, was dictated by availability and cost. We found that the diffuser and tent were affordable and especially important components since they allowed us to vary lighting for different material types (Kaufmann et al. 2015: 225).

The software package that we employed was Agisoft PhotoScan 1.3. The PhotoScan Standard Edition provided the majority of requisite functionality, but added features in the Professional Edition were occasionally necessary to tame the most obstinate models (Agisoft 2017a, 2017b). Although a more complex and expensive rig and software package[7] may have produced even higher quality results, the total cost for purchasing these did not exceed $1,000 (USD), making this rig and software an attractive option for small museums and archaeological projects. In addition, a cheaper camera and free

7 As of February 2018, the cost of an Agisoft 1.3.2 Standard Edition license ranges from $59–$179 (USD).

software (see, for example, Falkingham 2012) now places basic photogrammetry within the hands of many low-to-no budget museums and cultural heritage agency.

To produce models with this rig and software, artefacts were first photographed in multiple chunks (Agisoft 2017a, 36–39). An Abó Polychrome Majolica sherd, a type of pottery made predominantly in Mexico between AD 1650-1750 (Lister and Lister 1974), will be used to illustrate our process throughout the rest of the paper (Figure 5). Typically, this meant vertically rotating the object once or twice so that two to three separate sets of photographs, or chunks, were produced. For each chunk, the general procedure was to photograph one horizontal object rotation straight on (~0°–20°) and one horizontal object rotation from a raised angle (~45°). The size of the object necessarily impacted the placement of the camera. Our objects ranged in size from approximately 7 to 50 cm. We did not have success with anything smaller, which is likely to require a different approach (Marziali and Dionisio 2017).

With a manual turntable, we attempted to take a photograph every 10° of rotation so that an ideal chunk would result in 36 images straight on and 36 images from a raised angle. Others have experimented with fewer photographs per object rotation (Falkingham 2012; Kaufmann, Rennie & Clement 2015), but as a rule of thumb, 36 photographs worked best in our experience. More than 36 meant more time was devoted to photographing, masking, and model processing without any clear gains for our educational and outreach purposes. Fewer than 36 photographs reduced initial time investment, but frequently left one or two underdeveloped portions in our models that ultimately required reshooting anyway.

To aid the software's photographic alignment of each chunk and to protect the artefacts, a patterned foam block was used to support each object. Upon each side of the block, an outlined X in a distinct colour was drawn and the top of the block could then be cut to cradle each object (Figure 5). This block acted as an extra visual feature with which Agisoft could match the overlap between photographs; therefore, its presence was especially necessary for monotone and uniformly shaped objects that provided fewer distinct visual markers. Although our blocks were handmade out of convenience and frugality, patterns can also be printed and more formal, permanent, and aesthetically pleasing blocks can be created. In many ways, the use of this block serves a function equivalent to the coded targets used in modelling archaeological excavations and architecture (Sapirstein 2016).

The background of each photograph was next masked out so that only the artefact and patterned block remained. The background colour was typically either white or black, depending on which colour provided the best contrast with the object (Guidi et al. 2015: 343). An attempt was made at using a green background and programmatically removing it, but it was ineffective; the green was found to reflect off of objects, giving the final model texture a strange tint, and the programmatic removal of the background blurred object boundaries, resulting in low-quality models. The worst result of a green-screening experiment was a model of an oxidized pewter goblet, which likely belong to one of the Plate Fleet's wealthy passengers. The green reflection on the object's tarnished surface resulted in a model with fuzzy edges and with a colour similar to green, oxidized copper rather than black and purple oxidized pewter. Changing to a white background and manually masking each photograph produced a better result (cf. Guidi et al. 2013: 879–881). Still, it is worth further exploring the conditions under which a greenscreen will work as green backgrounds have been successfully employed by others, such as Kaufmann, Rennie, and Clement (2015). Reducing the amount of manual masking is one major avenue for speeding up the creation of models and for making the process more accessible to understaffed institutions and museums.

Once masking was completed, we aligned each chunk's photographs in Agisoft PhotoScan with settings of High Accuracy, Pair Preselection, and Constrain Features by Mask (Agisoft 2017a: 9–11). If alignment was successful, which was immediately apparent, a sparse point cloud existed that mimicked the general form and colour of the object and the patterned block (Figure 6). In the case of unsuccessful alignment, we checked for low-quality photographs, incorrect masks, or took additional photographs before trying to realign. Points in the sparse cloud with high reprojection error were removed using the Gradual Selection Tool (Agisoft 2017a: 29–30) and camera alignment was then optimized (Agisoft 2017a: 24). Each chunk was then processed into a

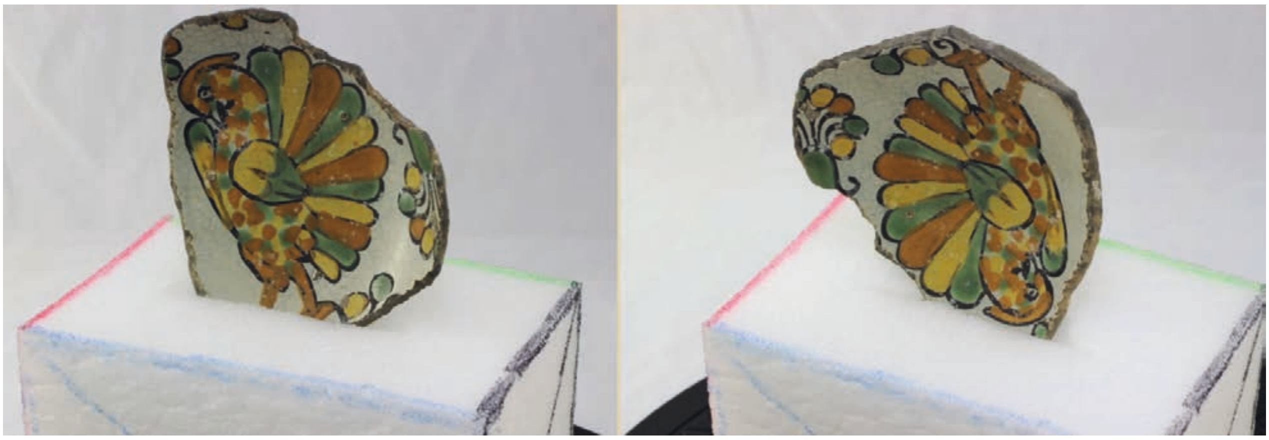

Figure 5. Each object was photographed in chunks. The patterned foam block aided the software's in detecting overlap between rotations within a chunk and thereby aligning photographs in three dimensions. This shows the two chunks used to build a model of the Abó Polychrome Majolica Plate.

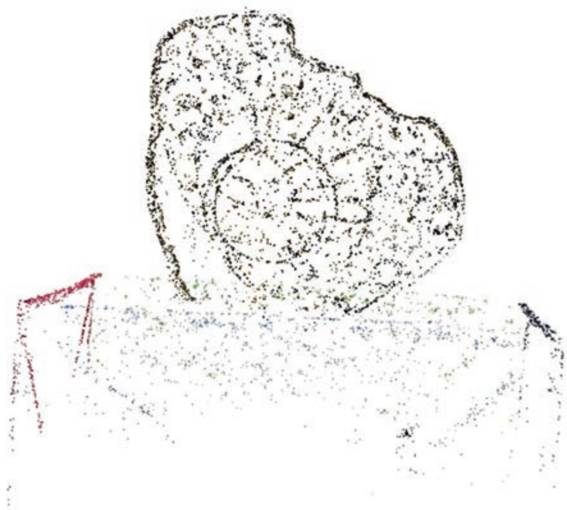

Figure 6. A sparse point cloud after the photo alignment of the first chunk of the Abó Polychrome Majolica Plate.

Figure 7. The two dense clouds of the Abó Polychrome Majolica Plate have been aligned, but the patterned blocks have not yet been deleted from the dense clouds. Note that spurious points right of the plate have not been removed in this example for illustrative purposes.

high-quality dense cloud using aggressive or moderate depth filtering (Agisoft 2017a: 12–13). Spurious points were commonly introduced during this stage (Kaufmann, Rennie, & Clement 2015: 226), and each dense point cloud required cleaning, both manually and using the built-in Select Points by Color tool (Agisoft 2017a: 30–31).

Each chunk's photographs were next manually masked a final time to remove the patterned block and any problem areas on the object itself, especially small patches of high reflection, which found would negatively impact texture creature. The dense clouds of each chunk were then aligned to one another (Agisoft 2017a: 37) based on the fully masked photos (Figure 7). Masking out the patterned block ensured that Agisoft did not attempt to incorrectly align the chunks' dense clouds using this part of the photograph. Once the dense clouds were aligned properly, the patterned block was itself deleted from the dense clouds. The aligned chunks' dense clouds were finally merged into a single point cloud that represented the entire object. On the rare occasion when dense clouds did not align properly, manual alignment was attempted in PhotoScan Professional; however,

	x3dom	SketchFab
Technology	JavaScript Framework	Online Viewer and Model Host
HTML Implementation	<x3d> tag with child tags	<iframe> tag
Customizability	Highly customizable through JavaScript and DOM	Some customization through JavaScript API, but has cross-site scripting limitations
Difficulty of Implementation	Moderately easy to implement basic functionality	Very easy to fully implement
Hosting	Hostable anywhere	Hosted only by SketchFab, but has a RESTful API
Cost	Free and open-source	Free in certain instances

Table 2. A comparison of x3dom and Sketchfab.

we found that failure to align two chunks typically meant that one of the two had been poorly photographed or incorrectly processed.

Lastly, a high-quality mesh was built from the merged dense clouds. Typically, this first consisted of one million faces, but the number was often pared down to appropriately balance mesh definition and file size (cf. Guidi 2015: 344–346). To cover the mesh, an averaged or photo-mosaiced texture (Agisoft 2017a: 14–16) was created from the fully masked photos. In a manner similar to the mesh face count, we started with a texture size of 10,000 pixels and repeatedly reduced this number until reaching a subjectively reasonable balance between texture definition and file size, which was an especially important concern for displaying these models on the web. An averaged blending mode was often best for objects with gloss or high sheen, while a photo mosaic blending mode provided higher definition for matte objects. When completed, the model was saved and exported in OBJ format with a JPG texture.

Run Aground: Displaying 3D Models Online

The problem of how we would disseminate these 3D models to a web audience existed concurrently with our unravelling of the photogrammetry process. Our attempts to display models online in a robust, scalable manner hinged on a choice of two technologies: x3dom[8] and Sketchfab[9], both of which have been used for displaying cultural items online (Lloyd 2016; Santos et al. 2014: 10–13; Ubik and Kubišta 2016; Unar and Patoli 2016). From a technical perspective, if you are using a modern browser, neither x3dom nor Sketchfab requires the once-obligatory download of a browser plugin to display 3D models, but the two still offer disparate strengths and weakness, which were at first difficult for us to gauge within the scope of our goals (Table 2).

Because of its high customizability, hosting-neutral nature, and open-source codebase, our initial leaning was towards using x3dom. When a diktat was then handed down by the State that we could not use Sketchfab since the company might own and commercialize our models, our settlement on x3dom was fixed. Yet, after building a proof-of-concept site around x3dom's JavaScript library, we found that while it met our basic needs, it would not offer the range of functionality that we envisioned without significant and time-consuming customization, which is not practical for many institutions. After a thorough review of Sketchfab's Terms of Service and a clear demonstration that we retained ownership of our content, we were permitted to move away from x3dom and implement a second proof-of-concept using Sketchfab. While certain elements of low-level customization were lost, in its place we gained a ready-made viewer that displayed high-quality models (Figure 8). Perhaps Sketchfab's most attractive features to us were out of the box lighting, built-in model annotations, and a RESTful API with which we could pull and push model data in JSON to and from Sketchfab's servers (Ubik and Kubišta 2016). Moreover, Sketchfab is built to work across devices, which solves the tricky problem of displaying 3D on mobile devices (di Benedetto 2014). As a result, after FLBAR acquired a free cultural institution license that allowed unlimited hosting, we resolved that our current and any future exhibits would use Sketchfab. Legitimate ques-

8 http://www.x3dom.org [accessed 27 February 2018]. The name is nonsensically pronounced "x-freedom."

9 http://www.sketchfab.com [accessed 27 February 2018].

Figure 8. The completed models loaded in SketchFab of the sanctus bell, grenade and fuse plug, and polychrome plate shown previously (see Figure 2).

tions remain, though, about the long-term viability of this decision. Since Sketchfab is as a third-party host of our models, future issues can always arise if the company is bought out, moves to a paywall, or goes defunct. As with other digitized content, the appropriate, long-term storage and documentation of 3D models is an ongoing issue.

The Swim for Shore: Building the Website

Since the State of Florida uses Microsoft Azure for hosting, we built the structure of the online 3D museum in ASP.NET Core. Instead of designing a static site, which was certainly possible, we used .Net MVC (model-view-controller), mixing in static, purely descriptive content when necessary. Both the gallery and individual model pages relied on Sketchfab's RESTful API to pull names, descriptions, thumbnails, and links, based on unique model IDs. This permitted content and models to be changed on Sketchfab by non-technical users and additionally centralized the storage of all model data.

The method of generating the gallery and presenting the models to end-users was built with the creation or addition of future exhibits in mind. When a client request for the model gallery is received by the controller, a server-side JSON array of collection names and model IDs is parsed, and the data for each model, including its thumbnail, is retrieved via a server-side GET request to Sketchfab's RESTful API[10]. The controller then builds these data into a view and returns it to the client. Since all styling is well separated into independent CSS files and a JSON array controls the gallery, exhibits can be changed or new exhibits can be quickly built.

The site's individual model viewer, too, follows the same principle; the controller dynamically builds a view for each model based on the model id passed in the client's request. Additionally, a major advantage to this approach rather than a static HTML approach is that Sketchfab relies on Markdown syntax for text descriptions. This again means that a non-technical user could style a model's description or annotations directly through Sketchfab with no regard for how CSS code or the server is structured. When the Markdown is retrieved, the controller parses it and passes proper HTML to the view.

Surviving the Wreck

The time from conception to completion was not short; it required approximately 12 months of experimentation with a staff of four working only sporadically, as time allowed. Once we had developed our workflow, a new model could be created within a few days, during which most labour was spent cleaning dense point clouds and masking photos. Discovering ways to reduce these two tasks would greatly increase the pace of model creation. Not only did our free dive into photogrammetry present a steep learning curve, but with limited staff, we had to fulfil many other conservation and curation functions as we also worked towards an online 3D museum. The long pro-

10 In deployment, the model data is actually cached on the server for 7 days to speed the return of content. The final site was intended to be deployed in July 2017; however, the cogs of Florida State's government move at their own, unpredictable speeds.

Figure 9. The galleries, in this case the one on trade goods, were generated dynamically on the server from a JSON array of model IDs.

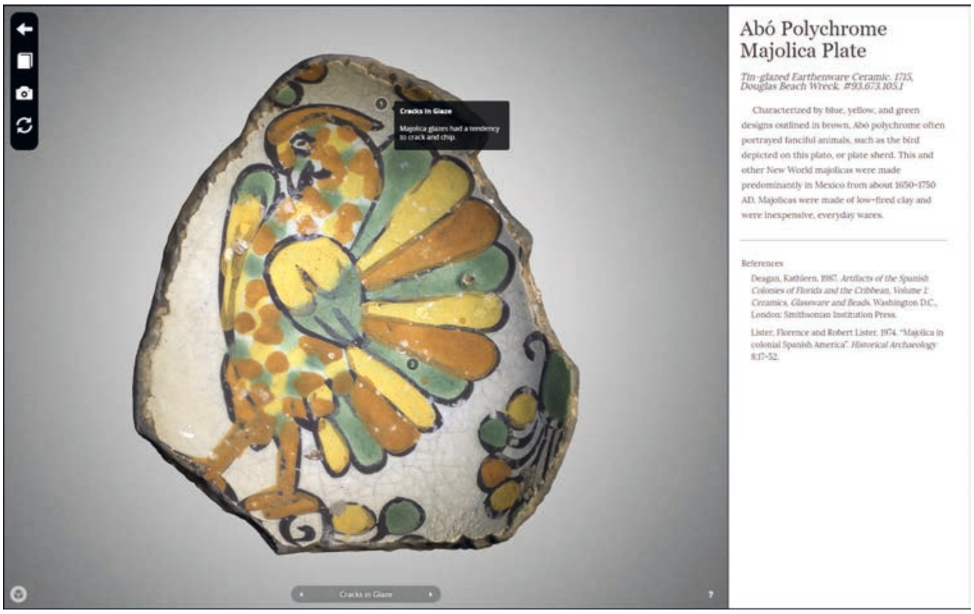

Figure 10. The model viewer was heavily customized and pulled its data directly from Sketchfab through its RESTful API. The final view of the Abó Polychrome Majolica Plate is seen here with its annotations and descriptive sidebar.

cess of mistakes and mishaps, though, led us to develop streamlined and reusable methods, and to design a scalable codebase upon which future exhibits can be built for the people of Florida. The successful completion of this project was ultimately not about expensive equipment or abstruse knowledge, but rather patient experimentation. Many questions and avenues for exploration remain open with the use of photogrammetry with cultural materials (e.g., Agosto and Bornaz 2017), but we hope that our achievement encourages any individual or organization with similar goals and limited funding to persevere and that this knowledge of our process will prove instructive to them.

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Archaeological Practice and 3D Modeling: A Medieval Ceramic Assemblage from Nemea, Greece

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Abstract

This paper explores the link between archaeology and the digital humanities, especially the adoption of 3D modeling technology, which is becoming an integral part of archaeological practice. Here we present a case study, a sample of 3D models from a large collection of well-preserved medieval ceramics from the excavations of the Sanctuary of Zeus at Nemea, Greece. This growing digital collection can illustrate the advantages, potential, and challenges presented by the incorporation of 3D technology into archaeological practice. 3D modeling technology can facilitate documentation, interpretation, and publication of archaeological datasets. However, the longevity of these datasets remains uncertain and require extensive dialogue and collaboration, as storage space requirements, support of current digital infrastructure, and long-term data accessibility and preservation are matters that do not have standardized solutions. More effort needs to be invested in preserving these large datasets before 3D modeling can become fully incorporated into archaeological practice.

Keywords: archaeology, 3D modeling, laser scanning, medieval ceramics, Greece

Introduction

This paper was presented in the CAA 2017 session "Exploring the Symbiotic Relationships of Archaeology and Digital Humanities." As the session's description emphasizes, archaeology is a discipline that is inherently spatial and temporal. It is also inherently interdisciplinary and fits comfortably within the Social Sciences, as well as the Humanities. It is closely affiliated with anthropology in North America but in Europe has a strong link to History and the Humanities. We consider this plasticity and interdisciplinarity as a strength rather than a weakness of our field.

Archaeology also cuts across the natural and computational sciences. These are real strengths that make archaeology one of the core fields in the transdisciplinary digital humanities. Archaeology was always among the first, along with geography, to incorporate new methods and tools, such as spatial analysis and GIS, which added new dimensions, and facilitated the documentation and analysis of spatial as well as temporal aspects of human settlement. New directions soon emerged, such as landscape studies, a multidisciplinary research area, where archaeology played a vital role (e.g., Ashmore and Knapp 1999; David and Thomas 2008; Muir 1999; Ucko and Layton 1999).

As new technologies, especially 3D technologies, have become widely adopted, archaeology has become a main contributor to Digital Humanities. This give and take, is a true symbiotic relationship between the two that has led, again, to new, multidisciplinary research areas, such as Digital Cultural Heritage. We can offer observations on the development of this fruitful and symbiotic relationship between archaeology and the Digital Humanities in our own institutions. The University of Nebraska-Lincoln (UNL) has been a leader in the field of Digital Humanities. When the Center for Digital Research in the Humanities was established, a decade ago, the core disciplines which contributed to the dialogue at the time were text-based disciplines, mainly English and History. However, it did not take long for archaeology to become one of the core Digital Humanities members and contributors, as interest, among students, and strong candidates with well-developed digital portfolios, led to the hiring of four archaeologists, in anthropology, art history, and classics, within the span of two years.

In this paper we reflect on the impact that these new developments had on our own work, as an example of the transformation that Digital Humanities approaches are bringing to established forms of scholarship. Here, we report on the ongoing experimentation with 3D modeling methods, in particular laser scanning, and their application to archaeological collections.

3D Modeling and Archaeological Collections

In the last 15 years the adoption of 3D modeling methods in archaeology has accelerated. These methods have found wide applications in the field and the laboratory and have brought rapid change to established practices (e.g., Forte et al. 2012; Olson and Caraher 2015; Olson et al. 2013; Remondino and Campana 2014). This new technology has also led to the growing digitization of archaeological collections of a wide variety of artifacts (e.g., Grosman et al. 2014). Some of the commonly discussed benefits that have accompanied the adoption of these new tools are increased measurement precision, ability to reconstruct artifacts (e.g., Barreau et al. 2014; Kampel and Sablatnig 2003; Tsiafaki et al. 2016), evaluation of morphological variability (Bretzke and Conard 2012), and ease of investigation, since the digitized objects represent accurate copies of the originals (Olson and Placchetti 2015). Another major advantage is that this technology facilitates virtual preservation and digital data dissemination. These qualities have led to the adoption of 3D technology by museums to enhance exhibits and provide novel virtual educational experiences (e.g., Payne et al. 2010; Sylaiou et al 2009).

Here we focus on the application of 3D modeling methods to the study and analysis of archaeological ceramics. Archaeological ceramics are one of the most common and important categories of artifacts, as they provide information on chronology, and cultural context. Because pottery is found in fragmentary condition, its documentation is labor intensive, as each fragment has to be described, measured, drawn, photographed and classified. The study of ceramics has benefited from the development of 3D modeling methods. The advantages of 3D technology over earlier methods are significant as they provide considerable support to traditional drawings and 2D recording and documentation methods (Ebolese, Lo Brutto & Burgio 2017).

Several studies have demonstrated that 3D modeling is not only more accurate than manual illustration, it also provides more information, and is actually a more efficient method. Karasik and Smilansky (2008) used 3D scanning technology to identify the rotation axis and profiles and obtain models of more than 1000 pottery fragments from several sites and time periods. They concluded that it was more cost effective compared to traditional methods. This and other studies have utilized 3D scanning for accurate data acquisition, including 2D profiling, and the calculation of attributes that are harder to measure by traditional means, e.g. volume, surface area, and symmetry.

Furthermore, digital libraries of 3D models of artifacts have become a reality. Early efforts (e.g., Rowe et al. 2002) aimed to develop a storage, archival, and sketch-based query and retrieval system for 3D objects. The process and results provided a model for a digital library of 3D data for further study and analysis. Another similar project, the Ceramic Technologies Digital Library (CTDL), involves the creation of an integrative, web-based database on medieval ceramic technology from Central Europe, particularly the Germania-Slavica area (ca. AD 600–1400). It applies 3D scanning technologies to ceramic vessels, in addition to analytical software for vessel symmetry. The primary goal of the CTDL project is the creation, support, and long-term curation of a digital library (Simon et al. 2008). A more recent project is "Digitizing Early Farming Cultures" (DEFC), which has standardized and integrated research data of Neolithic and Chalcolithic sites from Greece and Anatolia (c. 7000–3000 BC). The digital exhibit includes a 3D pottery gallery and associated metadata (Štuhec et al. 2016; https://defc.acdh.oeaw.ac.at/).

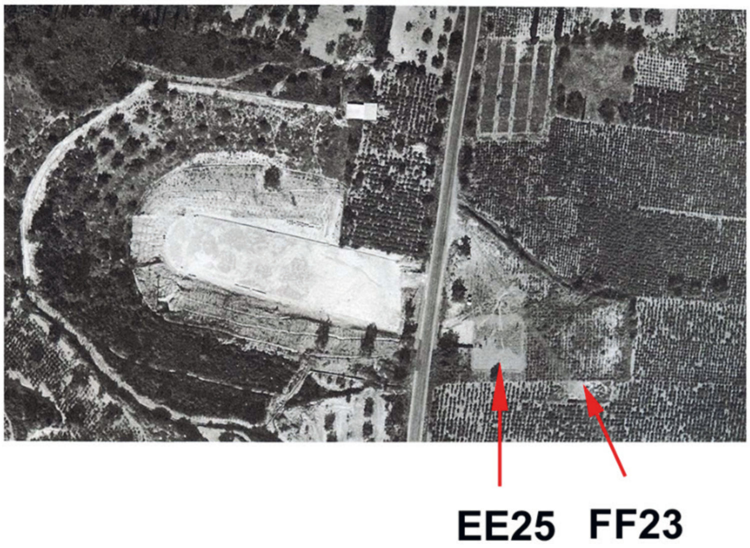

Figure 1. Nemea Stadium, aerial view: arrows indicate the location of grid squares EE25 and FF23.

A Case Study from Nemea, Greece

Next, we reflect on the impact that these new technologies had on our own work as an example of the transformation that 3D modeling methods are bringing to established archaeological practices. The case study is a collection of medieval pottery derived from the excavations at the Sanctuary of Zeus at Nemea, carried out by the University of California-Berkeley in the 1970s and 1980s. The pottery came from a series of closed deposits, from the Nemea Stadium, which were excavated in 1975 and 1980 (Miller 1976; Miller 1981). These deposits yielded ceramics dating mainly to the 12th and 13th centuries CE. The excavated pits (located in sections FF23 and EE25, Figure 1) stand out among the deposits with medieval material from the Nemea excavations because they produced large quantities of well-preserved ceramics, diagnostic fine wares, as well as coarse wares. This material is being studied in order to identify representative shapes, styles, and dates, which are the backbone for further analysis. This assemblage can also serve as a reference guide for other projects, since comprehensive studies of ceramics from the medieval period in Greece/Aegean are few compared with those dating to earlier times, i.e., the Bronze Age and the Classical and Roman periods. Thus, the adoption of 3D modeling methods was part of the overall research goals, to provide a better form of visualization for the study and publication of medieval ceramics from Nemea. Furthermore, creating 3D models of representative types of medieval ceramics provides additional options that can facilitate the analysis and sharing of results. The selection of ceramics for 3D modeling was based on the following criteria:

- Fragments that represent the most common types of decorated and undecorated wares;
- Fragments that represent less well-known types of wares;
- Sherds that exhibit variation of basic features in shape and size;
- State of preservation: preference is given to well-preserved fragments that can provide information about the main attributes of the vessel;
- Significance of a particular type for establishing a classification, especially of coarse wares.

For decorated ceramics of this time period, there is an established classification scheme based on decorative techniques, e.g., glazed, painted, incised, slip painted (Morgan 1942). However, there is little published comparative material for medieval coarse wares, which constitute the majority of the finds (e.g., MacKay 1967). Thus, the Nemea collection can also contribute to this end, to document coarse wares

Figure 2. Nemea FF23.10.50 siphon handle 3D model.

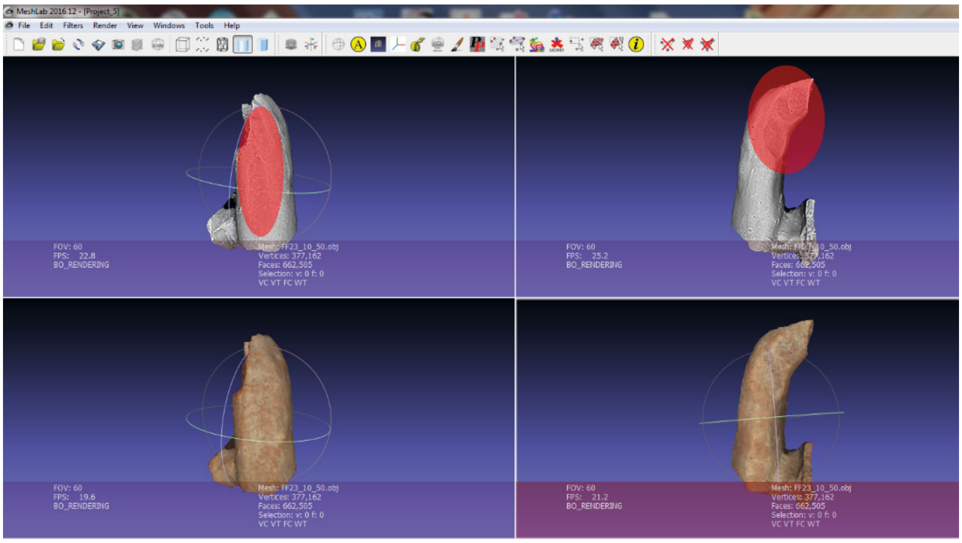

Figure 3. Nemea FF23.10.50 3D model in regular and radiance scaling rendering. The red ovals indicate areas with finger marks.

that were common in rural areas and facilitate the development of a typology.

3D Modeling and Archaeological Analysis

In the course of three summers, over two hundred 3D models of diagnostic ceramics have been completed. The 3D models were created with a Next Engine 3D laser scanner (Brown 2010; White 2015). It is a portable, affordable scanner, which can accurately record small to medium sized objects, with a precision of 0.13–1.66 mm (Polo and Felicísimo 2012). The texture is not high resolution, for example, it is not as good as the texture that photogrammetry provides. However, this equipment produces high-fidelity models in a fraction of the time required for photogrammetric processing. Multiple views are needed to create a complete model. The 3D model requires editing (trimming, aligning, fusing) and, depending on the complexity of the object, it can take from half hour to two hours for a complete edited model. The scanner records surface lines, indentations, breaks, imperfections, etc. that may facilitate different types of analysis (e.g., manufacturing methods). Thus, the specific traits of the NextEngine 3D desktop laser scanner make it very useful to archaeological research, since it is lightweight, affordable, easy to operate and accurate. It has been used successfully to create 3D models of a variety of archaeological materials including ceramics (e.g. Kaneda 2009; Means, McCuiston & Bowles 2013).

The production of high-fidelity 3D models is a

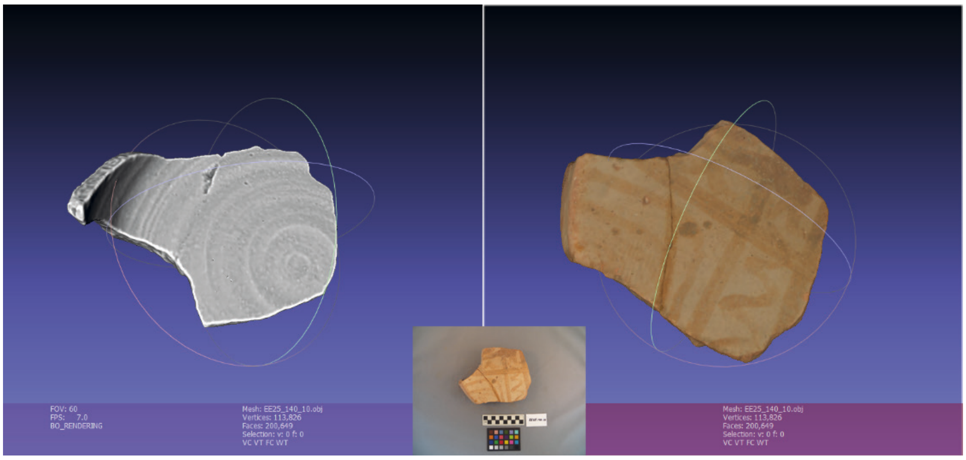

Figure 4. Nemea EE25.140.10-3D model in regular and radiance scaling rendering.

starting point for further analysis and interpretations of the ceramic material. These models enhance the detailed examination of the artifacts, and aid classification and documentation of the stylistic variability within each type. Also, the 3D models assist in the study of manufacturing techniques, facilitate measurements, and reconstruction of representative types. They offer new possibilities, as one can examine details that are not visible in 2D photographs or even on the artifact itself, when viewed under standard lighting conditions. For example, a unique artifact in the collection is a large fragment of a hollow tube (Nemea FF23.10.50; Figure 2). This interesting object was part of a special vessel, a siphon, designed to draw liquids through suction from large containers. The handle/tube was handmade and its surface preserves finger imprints from the manufacturing process. However, these features become visible only when the 3D model is processed with special filters, such as the radiance scaling filter available in Meshlab, which enhances the 3D model's concavities and convexities (Figure 3; Vergne et al. 2011).

Another unusual shape is a flat-bottom flask (Nemea EE25.140.10). The base is decorated with matt-painted intersecting lines and zig-zags. It is a fragment of a special type of water-transporting vessel known as an *askodavla*, a flask derivative (Bakirtzis 2003). This vessel was manufactured on a potter's wheel, in separate pieces that were then joined together. The base interior preserves features, wide concentric grooves/lines that resulted from the manufacturing process on the wheel. These become visible when the 3D model is processed with the radiance scaling filter (Figure 4).

A 3D model of a chafing dish, a more common shape, can also be enhanced with shading tools in order to accentuate its surface features, which consist of incised and relief decoration (Nemea FF23.10.45, Figure 5). This shape combines a shallow dish set on top of a stand with a lid; it was used to serve food and keep it warm (Sanders 2003). Multiple views of this fragment are needed in order to document its characteristics and the methods of manufacture for this type of vessel. Thus, the 3D models improve this process, provide detailed views that reveal manufacturing methods, facilitate the classification of this pottery, as well as comparisons with similar material. Furthermore, by exporting the 3D models in different formats and converting them to widely supported files such as PDF, a variety of views and cross-sections can be generated by the user. For example, the 3D model of a globular juglet with sieve can be shown with its cross-section at different points to allow accurate documentation, identification and comparison (Nemea FF23.10.75, Figure 6). Thus, documentation is a critical phase for the classification of archaeological ceramics, especially those that have not been studied extensively.

The incorporation of 3D technology has aided this research project. At this time of transition from well-established practices of 2D drawings and photographs of artifacts to 3D recording, it is fair to say that the 3D models offer a number of advantages: 1) The 3D models are high fidelity digital reproductions, superior to 2D renderings. 2) They provide visually effective means for documenting the composition of the assemblage. 3) They provide a substantial amount of information for the viewer that the researcher does not filter. Many applications of 3D modeling apply primarily to display and

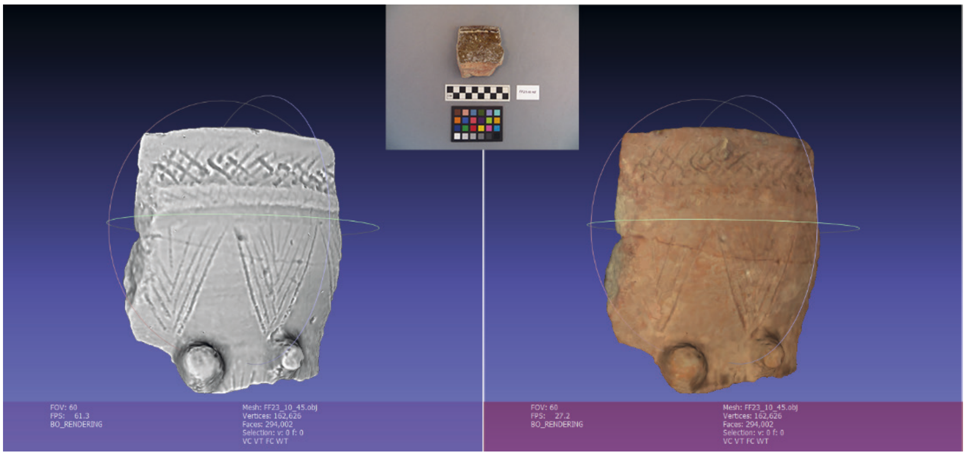

Figure 5. Nemea FF23.10.45, chafing dish 3D model in regular and radiance scaling rendering.

presentation of data (Newhard 2015:12). However, visualization is intertwined with analysis, and, as Opitz (2015:77) suggests, is part of the interpretive process. The 3D modeling process produces digital reproductions of artifacts that can be used for a variety of typological, functional, and other kinds of analyses. So far, we have highlighted typological aspects and manufacturing methods. To date these deposits from Nemea are the key in our effort to refine the chronology, especially of coarse wares, and reconstruct daily activities at the site. The next step, however, will be to concentrate on social aspects, including food preparation, storage, and the reconstruction of consumption patterns and regional trade networks. The 3D models provide high-quality information to achieve these goals and are central to the next phase of the project, dissemination. This is a significant archaeological assemblage that, so far, has been available only to specialists. Currently, a substantial selection of 3D models from this archaeological collection is readily available through Sketchfab. In the near future, the whole assemblage will become available via a digital archive using the 3D Heritage Online Presenter (3DHOP) (Galeazzi et al. 2016; Potenziani et al. 2015). Although the immediate plans are for a digital archive that will highlight this particular collection, there is a need for a broader initiative, a database that will bring together material from several regions. Such an effort can provide solutions to a common challenge, the identification and comparison of similar material from different sites and regions. The development of a multi-regional digital archive can streamline the search for particular types of medieval pottery using standardized terms. It will facilitate different types of analyses and ensure that the next phase of research stands on firm ground.

Digital Preservation and the Future

3D technology has a transformative role when it comes to sharing of results and inviting public interaction. Digital modeling is becoming as indispensable to archaeology and museums as photography in the late 19th century (Garstki 2016). Many museums are investing in engaging exhibits which incorporate 3D technology. One of the notable examples is the Smithsonian's X 3D project (3d.si.edu), which makes available to the public 3D models of a wide variety of objects from its collections that can be downloaded and printed (Rabinowitz 2015:27). This is one of the novel qualities of 3D technology, that the digital models can be duplicated easily and displayed in multiple locations. 3D digital artifacts offer accurate, high quality data to researchers, without the need to visit museums or storage facilities or to handle original finds. Thus, they enhance preservation, as the digital copies provide faithful substitutes of the artifacts. The act of creating a 3D model is a step towards digital preservation. A 3D model can potentially serve as an enduring record of an artifact. So, certainly, artifact analysis, and digital preservation are benefiting from 3D technology. 3D modeling methods are generating novel kinds of datasets and are creating a new category of objects, "digital surrogates" which have their own independent reality and require their own documentation and explanation

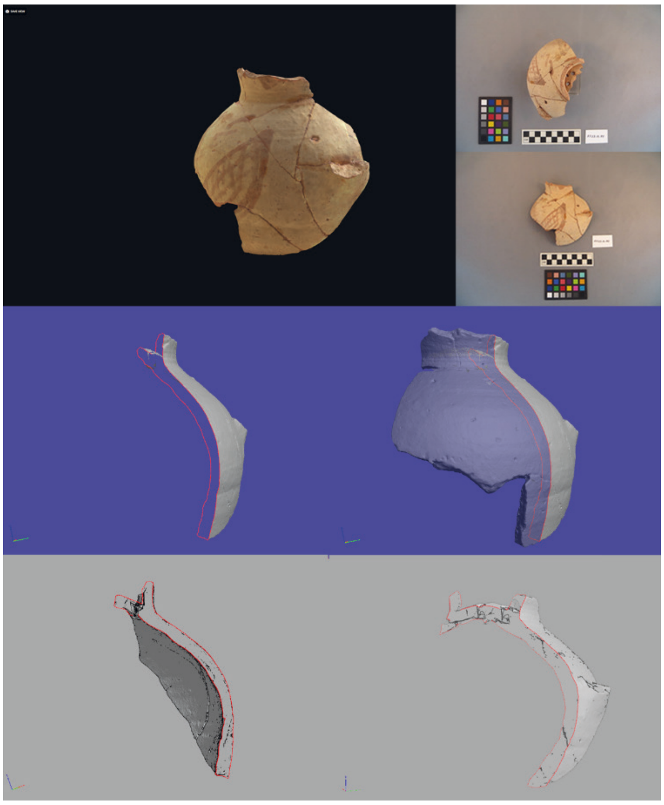

Figure 6. Nemea FF23.10.75, juglet with sieve, 3D model and cross sections at different points.

(Rabinowitz 2015:36). "Digital surrogate" is a term used in libraries and archives to refer to any digital representation of a work that exists in the physical world (a thumbnail, a metadata record, a digital image). More commonly, however, the term indicates a faithful digital copy that seeks to represent an analogue original as accurately and in as much detail as possible (Rabinowitz 2015:29).

Many questions remain, as we are still assessing the impact of digital technologies, and 3D modeling in particular. For example, the longevity of these datasets remains uncertain, as storage space requirements, support of current digital infrastructure, and long-term data accessibility and preservation are matters that do not have standardized solutions yet, rather require extensive ongoing dialogue and collaboration. Rabinowitz (2015:34-36) offers four basic principles to guide publication and archiving in order to ensure the future scholarly usefulness of 3D digital surrogates. Some of these have become common practices, while others require the development of new tools: 1) Measurements: the models have to include some user-accessible information about scale and units. 2) Inclusion of raw data for reuse wherever possible. 3) Metadata: The raw data are of limited use without comprehensive metadata that indicate what the raw data represent. 4) Process history: Specific information on how a model was generated and processed.

Well-established initiatives such as Digital Antiquity and tDAR, the Archaeology Data Service (UK), and Open Context are providing leadership in the area of preservation, and long-term access to archaeological information (e.g., Clarke 2015; Kansa, Kansa & Arbuckle 2014; Niven 2017; Richards 2017; Stylianidis and Remondino, 2016). New initiatives, such as the Community Standards for 3D Data Preservation (CS3DP), aim to develop consensus on standards that include best practices, management, storage, metadata, access, copyright/owners and general workflows for 3D creation services and discoverability. This is an active area of research which in addition to the development of best practices, also addresses data sustainability, accessibility, and reuse (Richards-Rissetto and von Schwerin 2017). 3D modeling technology has become an integral part of archaeological practice. The challenge ahead is to find sustainable solutions that can ensure the continued use of these large and diverse datasets for future research.

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Geometry as Matrix of Construction of Roman Stone Bridges: The Augustus Bridge at Narni

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Abstract

The study of ancient Roman bridges embraces various disciplines and professions: engineers, architects, historians, archaeologists, and geologists. One of the first experiments completed by this research group was conducted on the Augustus Bridge at Narni: an integrated digital survey followed by the application of 3D digital modelling. Although only one of its four arches has been preserved, it can still be seen that the bridge was conceived on a large scale of technical complexity based on a precise knowledge that guided the choice of materials and architectonic solutions. The structure is immersed in an enchanting green landscape, which has for centuries attracted numerous scholars and artists. They have left us a precious iconographic heritage whose interpretation is still debated. As far as the geometry and proportions of the construction are concerned, to compare its present state with the original one, the structural ashlars of the bridge were modelled parametrically on the basis of transforming elementary geometric elements having adopted the Roman foot as the unit of measure.

Keywords: integrated digital survey, Roman bridges, proportion, measure, parametric modelling

Introduction

A large number of Roman bridges can be found on the territory of Italy. So far studies have been conducted[1] on the Emilio Bridge, the Fabricius and the Milvio Bridges in Rome, the Augustus Bridge at Narni, and the Roman bridge in Rieti. It is possible to affirm that each bridge is unique both from the figurative and material point of view and from the topographical context in which it is inserted. The present research has attempted to trace a methodological path of comparative analysis regardless of geographic proximity and construction technique[2].

It is precisely to pursue this objective that collaboration was initiated with Antonio Pizzo[3] who added to the repertoire of Roman bridges the Spanish bridges in Mérida, Alconetar, Alcantara, Segura, and Villa Formosa in Lusitania.

The bridges studied in the territory of Roman Lusitania (Hispania), documented with the same methodological and technical procedures as the bridge analysed in the present study, exhibit a set

1 The present state of the bridges was the objective of surveying the above mentioned ones with 3D shape acquisition technique. The Emilio bridge was the subject of the M.A. Thesis in building construction engineering and environment systems (LM24): the candidate for the degree was Giulia Umana with the thesis "Art and technique in the ancient stone bridges. The Broken Bridge of the Isola Tibertina", A.A. 2015/2016, supervisor prof.arch. L. Paris, co-supervisors prof. Arch. F Di Marco, eng. M.L. Rossi.

2 The research presented here is a part of a larger university research project focused on integrated digital surveying, the construction and virtual communication conceived as one of the means of cognizing ancient Roman bridges in Rome and its provinces. Apart from the authors of the present study, involved in the project are Prof. Paola Quattrini, Prof. Tommaso Empler and other collaborators.

3 Archaeologist and Cientifico Titular of CSIC (Spain) at El Instituto de Arqueologia (Mérida).

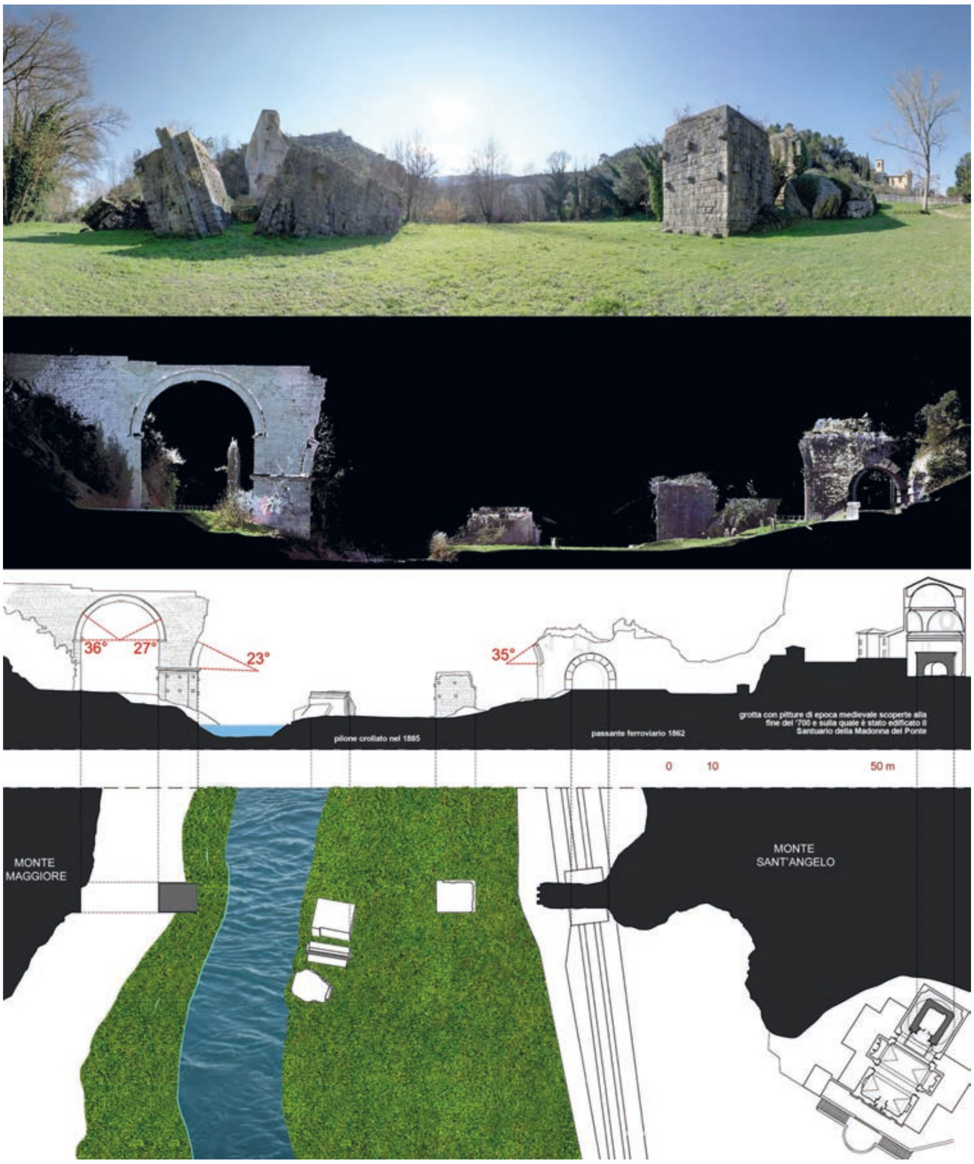


Figure 1. Ruins of Augustus Bridge in relation to the Sanctuary of the Madonna del Ponte and the cave inside it.

of common characteristics, which when analysed in detail yield information of considerable interest on the techniques applied, specialization of manpower employed, as well as on the transmission of technological knowledge in relation to architectonic models and materials used by the Romans. The data obtained in the regional setting, homogeneous from the historical and territorial point of view, could be considered as the frame of reference for case studies on Roman territories. Below we present the first fundamental piece of completed research, which is part of an ongoing project[4], on the famous Augustus Bridge in Narni, situated along an ancient route of Via Flaminia. Many hypotheses have been put forward as to the form of the bridge, the dimension of its arches, and original measures and proportions. This study attempts to provide answers to some of these questions. The research discussed here (be-

4 The present paper was presented at other conferences, among others, that of "The third centenary of the Sanctuary of Madonna del Ponte; a day of study" In Narni, 17.04/2015, supervized by the Center of Historical Studies in Narni and devoted to the initial stage of analysis. Among the participants were Wissam Wahbeh, post-doc FHNW University of Applied Sciences and Arts, Northwestern Switzerland and Pamela Maiezza, ph.d. Student from the Universitá degli Studi dell'Aquila. During the meeting an integrated digital survey of the bridge and of the Sanctuary together with their subsequent restitution were conducted. The second stage of analysis of the geometries and the proportions carried out on models two- dimensional and three-dimensional models of the bridge, finalized to define a reconstruction hypothesis and presented at the international conference "APEGA2016: Dibujar, Construir, Sonar. Investigationes en torno a la expresion grafica aplicada a la edification" at l'Universitat Jaume I a Castellon de la Plana, Spain, 1-2-3/12/2016.

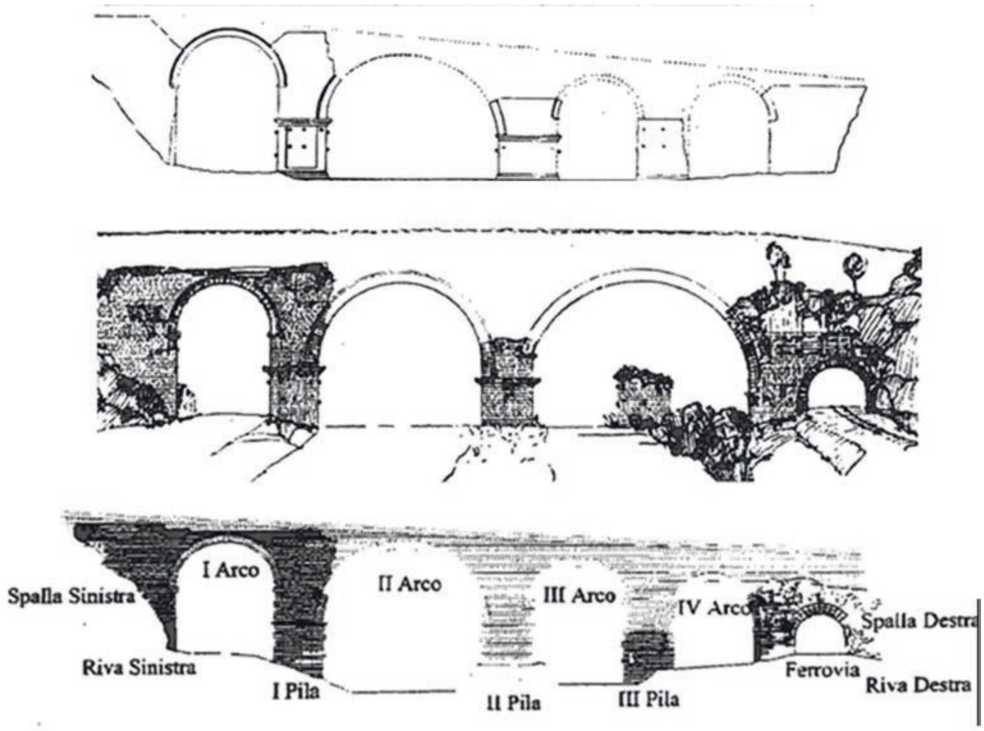
Figure 2. An engravingof Philipp Jakob Hackert (1737-1807), a small part of the iconographic heritage concerning the Augustus Bridge.

gun in 2015) extends the knowledge of the object of study, relating geometric and measurement aspects to structural ones as evidenced by the state of the ruins of the bridge.

Augustus Bridge and the Cave of the Sanctuary

In 27 BC, Augustus ordered the construction of a bridge across the Nera river valley to join two mountainous terrains: 1) the area of Monte S. Angelo to the north towards the plain of Terni, on the slopes of which there is today the Sanctuary of the Madonna del Ponte, and 2) the area of Monte Maggiore to the south, almost under the fortifications of the ancient city of Narnia (today's Narni). It is a strategic point that makes it possible to cross the river and join its banks. At the same time this area functioned as a kind of transition zonebetween the hilly landscape and the Terni valley. Thus, topographically, the relationship between the city and the landscape into which it is immersed has remained almost unchanged for 2000 years. The Augustus Bridge is an imposing work of masonry engineering with its four arches. Via Flaminia has remained until today one of the main arteries to cross central Italy.

Although in many parts the Via Flaminia corresponds to its ancient course, it is impossible to trace with precision its path at the point of the bridge, since between the final years of the 19th century and the Second World War, it was largely modified following the construction of hydroelectric plants and alternative roads. Numerous hypotheses have been put forward on this question over the course of centuries supported by 17th century discoveries that documented interesting pre-existing structures that could have been in some way connected with the course of Via Flaminia and the trail towards the cave of the Sanctuary of Madonna del Ponte with medieval paintings inside (discovered at the beginning of the 18th century). Recently a church has been built around the cave, which resulted in part of Monte Sant'Angelo being dug-up exactly on the side where the course of the Via Flaminia presumably ran. The erection of the Sanctuary was not the only work that influenced the layout of the landscape. In the 1860s, the bridge was also modified for the railway line Roma–Terni. For this purpose, a part of the substructure of the right abutment was demolished to make a new arch. In this way the right bank of the river was completely separated by the plain of Terni where today there is the residential area of Narni Scalo. Moreover, it functions figuratively as the fifth arch of the bridge, which changes completely the reading of the structure and



	I ARCO	I PILA	II ARCO	II PILA	III ARCO	III PILA	IV ARCO
EROLI	19.65	10	32.1	10	17	10	16
RICCARDI	19.5	9.5	32.4	10	16.92	10.48	15.6
ASHBY	19.6		32.1		18		16
BALLANCE	19.5		32		?		16
CECCHI	20.05	9.65	31.95	10.1	18.3	10.1	15.58
CHOISY	19.5		32.1		17		16
CESANELLI	19.5		32.1		43	-	-

Figure 3. Reconstructions of the original form of the bridge made by some scholars and reported in chronological order (the measurements are in meters).

the rhythm of the four arches of the original Roman bridge. In fact, the only arch that survived intact is the first one, just in front of the left abutment. After the collapse of the second and the third arch, the pillar which supported them tumbled down under the pressure of the river's waters in 1885. The problem of the second pillar and the lack of information as to its original position seem to be the main source of a succession of reconstruction hypotheses in most cases contradictory to one another. The objective of the present enquiry is to study in depth the positioning of the ruins of the Augustus Bridge in relation to a wider environmental context and with reference to previous studies (Figure 1).

Digital Survey of the Bridge Supporting of Verifying Reconstruction Hypotheses

The landscape in the which Augustus Bridge is immersed, particularly evocative for its natural beauty and for the ruins themselves, has for centuries attracted numerous artists and scholars. Precisely for this reason, we have at our disposal a continuously accruing iconographic repertoire documenting the bridge and its surrounding landscape from the middle of the 17th century until the end of the 19th century (Figure 2).

In these images the bridge in not presented as a work of engineering but functions as a part of the landscape (Tattoli, 2000). Some of these artists focused on representing the bridge, as if it were the fulcrum of the picture, others concentrated more on the engineering aspect of the structure with very realistic representations of documentary value, especially useful for attempts at identifying all the modifications it underwent over time. Moreover, because the ruins collapsed again and because of the inherent instability of the masonry structures that survived, many scholars treated the task of surveying the bridge as a means to program works of restoration. Hence, our iconographic heritage does not include only artistic representations but also scientific ones, which in most cases are accompanied by hypotheses on their original form. (Figure3).

The most recent survey, conducted under the supervision of Alberto Cecchi in 2003, was carried out with innovative topographic and photogrammetric instruments (Cecchi, 2003). It responds to many questions in a convincing manner, but overlooks some fundamental problems. Just like numerous scholars before him, Cecchi comes up with a different solution to the problem of reconstruction, based on a careful reading of data from the survey (Figure 4).

On these premises and considering the fact that Cecchi's survey can be integrated with new laser scanner acquisitions and photogrammetry, our research group came to the conclusion that it would be useful to carry out a campaign of digital survey. The first objective to achieve at the first stage of the survey was that to capture a unique point cloud integrated with RGB photographic values and topographic control points (Paris, 2015) that would include not only the ruins of the bridge on both banks of the river but also the whole area of the Sanctuary of Madonna del Ponte. This procedure allowed us to elaborate a model that related the whole Nera river valley to the ruins of the bridge and the interior of the cave. The survey stations, starting precisely from the cave, were positioned outside and inside the Sanctuary in order to reach the top of the right-hand abutment of the bridge, from which it was possible to take in the whole area, overtake the railway tracks, survey the ruins on the right bank of the river and finally survey the grand arch that survived intact on the left bank. One of the pillars adiacent to the river collapsed on July 17th 1885 when the river flooded, most probably due to its position in the centre of the riverbed but also for the lack of breakwaters. It was also shifted away from its original position by the sheer force of the water. Tumbling down, it broke into three blocks. The third pillar is well preserved, stable in its original position, and even though the upper cornice is lacking, its external parameters have been preserved perfectly. The second and the third arch, supported by the pillars described above, collapsed in 10503 also when the river Nera flooded. From that point in time, the Augustus Bridge appears in medieval documents as "the broken bridge." In order to provide the possibility to cross the bridge, a wooden scaffolding was constructed as evidenced by holes into which it was attached. It was but a temporary, expedient solution. A new bridge was built not far in 1217. Due to the difficult orographic situation at the point in which the bridge is coupled with the Monte Maggiore slope and where a new road to Narni was constructed in the 1960s, it was impossible for the moment to acquire information useful to carry out an in-depth study of the area where the Via Flaminia certainly ran behind the ancient nucleus of Narni. In total 31 scans were taken with the resolution of 10,000 points in the equatorial section. For the collimation of various point clouds, we decided for most cases to proceed marking out spheres of automatic recognition between adjacent scans. In some cases this was done manually by recognizing known coordinates surveyed topographically. Starting from the first elaboration of the point cloud it was possible to formulate some conclusions. We could deduce that the cave of the Sanctuary is not related to the bridge, neither in its the planimetric position nor in elevation, independent of the slant thereof. Moreover, it was clear that the pillars were all aligned and therefore the hypothesis that their position shifted, as was put forward in earlier reconstruction attempts, proved groundless. Visible in the first arch are fractures in its sides, similar to those in the other two arches: the second and the third arch collapsed because the pillar gave way under the pressure of water, but the first pillar had to be excluded from this pressure because it was erected in a place higher than the water level during these floods. Today the bow has a lowered key and corresponds to the sides at 36 degrees and 27 degrees at the springing line, compared to the side of the shoulder and that of the pillar. It was possible to establish the curvature of the second arch at the value of 23 degrees at the springing line. It was no longer horizontal as the pillar rotated by one degree in the vertical section. Hence we can say that the fissures in the surviving arch were caused by the absence of the second, the bigger one in the original design, which was most important for balancing out the shifts. After the second arch had collapsed, the second pillar inclined in this direction extending and making visible the consequences of the rotations in the arch.

In regards to the constructive elements of the ruins of the bridge, it is noticeable that the structure of the northern span of the bridge is hooked directly into the Monte Sant'Angelo and definitely is the most

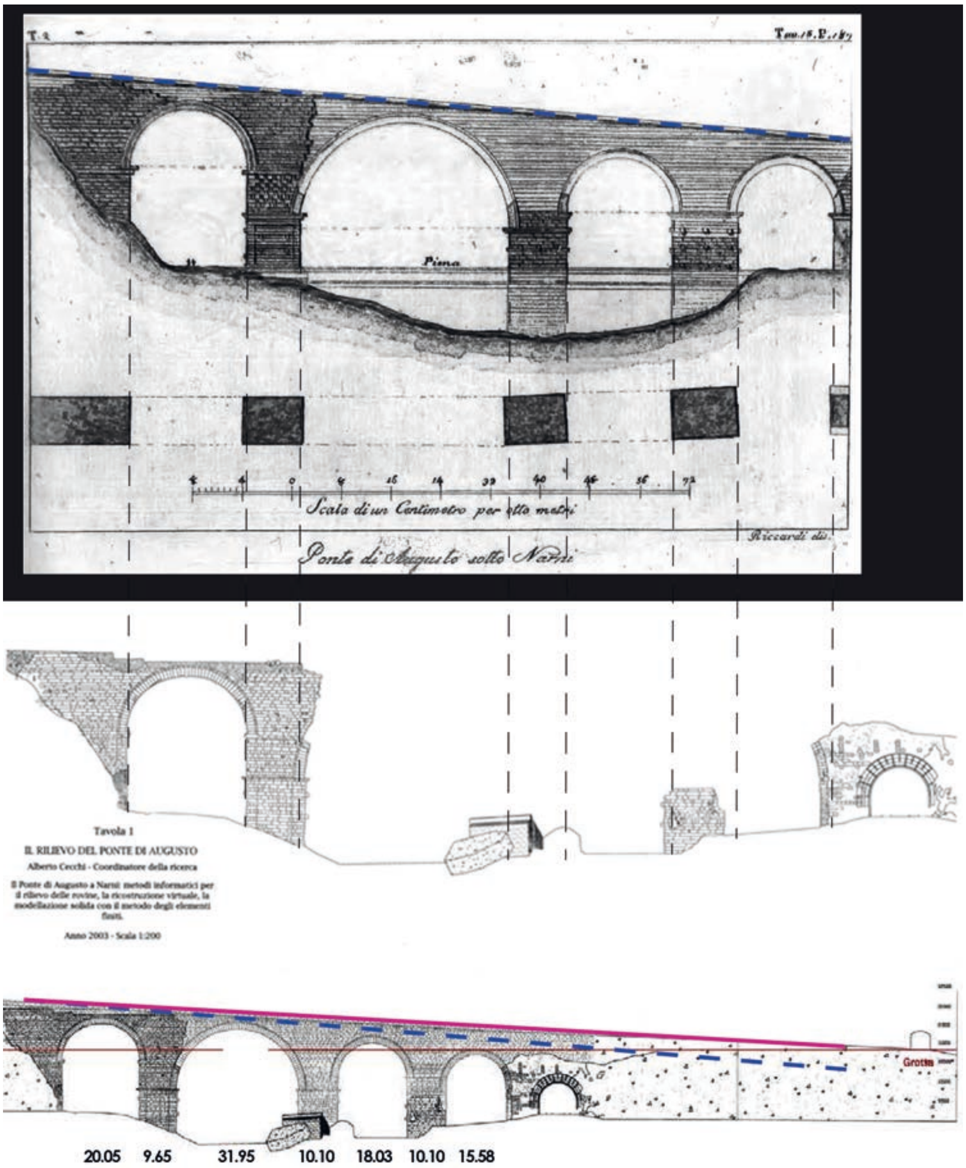


Figure 4. Survey and hypotheses for the reconstruction of the bridge by Eng. Giuseppe Riccardi in 1837. The differences in the springing line of the great arch, the declivity of the street and misalignment of the pillars are clearly visible (from Tattoli 2000). A comparison with Cecchi‘s survey. The dashed line represent the excessive slope of the road to Riccardi, compared with the slope.

degraded part of the bridge. One can see its nucleus as it is almost totally stripped of the stone layer that was removed when the railway line was being constructed. The arrangement of the blocks of the remaining side seems to be similar to the lower part of the left span. From an analysis of the remaining structures there are evident constructive and typological differences: the ruins of the fourth arch, which are interrupted on the right side at 35 degrees on the springer, shows a different method of assembling the blocks. This technique is probably posthumous to the first construction phase as it has 5 rings of parallel and alternating blocks, instead of an arc with a constant intrados. (Galliazzo, 1995).

The surviving arch rests on the left abutment and the first pylon. This pylon has a socle without rostra. It is endowed with a parament characterized by a regularity of alternating arrangements for the head and the cut of the keystones (pillars) as well as by an accentuated beveling of the ashlar, similar to the base part of the abutment. On two sides, upstream and downstream, there are frames. The data captured through the integrated digital survey were elaborated yielding 2D graphics and 3D models.

Models of the Bridge for the Purpose of a Reconstruction Hypothesis: From Discrete to Parametric Models

The main target of our research group, as stated above, is to verify different interpretations and versions of the same object, through 2D and 3D models for the purpose of extending the knowledge of architecture. In the previous paragraph we described the application of the discontinuous numeric model to achieve this particular goal. Another type of model that helped us towards this aim was that derived from a point cloud (the continuous polygonal model) we had recourse to in order to uncover forms and positioning. It must be said, however, that this model – in comparison with the one from which it was extracted – can only provide the factor of continuity, the principal feature of architecture, given that the same operations – enquiry and section – can be carried out on the point cloud.

On the basis of analyses carried out on models described above, we have constructed a continuous mathematical model which constitutes a synthesis of prevalently geometric character. It is a model of compromise between the numeric data, a faithful representation of reality, and an ideal geometric model that can be representative of a design idea. With respect to the form of the arches, we proceeded with a comparative reading of the data surveyed on the first arch partially preserved. Bearing in mind that the springing line is not horizontal, the growth of curvature parameters of the arch to the splitting point corresponding to the flanks have been calculated along the thickness of the surviving arch, with circles passing through three significant points obtained from the point cloud. The thickness has been analyzed in its totality through vertical planes of the arch placed at 10 cm intervals. In this way we obtained the first datum enabling us to determine the generatrix of the arch and put forward a hypothesis as to the position of the collapsed pylon. Since this is the most important factor of uncertainty, the form and positioning of other arches could be determined. Before the arches collapsed the bridge had the construction rhythm of four arches similar and dissimilar in some aspects. The reconstruction hypothesis was supported by geometric hypotheses – according to our analyses of the curvature of the arch ruins – as well as by the measurements of the geometries. Unlike other studies, instead of putting forward again the hypothesis of a decimal metric solution, whose values, as we have pointed out, are derived from a reading of the present state of the arches (which in the course of centuries were subjected to various and sometimes significant modifications) we sought a solution that would be somehow compatible and would be confirmed by the ancient unit of measure: the Roman foot (29.65 cm) This particular methodology was applied since in numerous work of architecture of similar dimensions, and mainly for ancient works of infrastructure, a correspondence with the entire values of the unit of measure had been observed. It was also noticed that the measure of the first arch was perfectly compatible with the third one. Identical measurement values of the diameter of the arch would be fully justified given how it was possible to optimize the yard in the construction of provisonal works. Thus the hypothesis has been put forward that the two arches had the diameter of 66 Roman feet, equivalent to 19.57 meters, while the biggest arch had the diameter of 104 Roman feet, i.e. 30.83 meters, and the fourth one – only 53 feet, i.e. 15.71 meters. (Figure10). These measures would be perfectly congruent with those surveyed. The collapse of the second pylon, documented already in the Renaissance, together with the fact that the presence of rostral pylons were also documented, strengthens the hypothesis of the river Nera having originally been much narrower, reaching only the second arch. This would justify the erection of only one central arch. Following major geological modifications the bed of the river could have enlarged so that the second pylon came to be significantly lowered and exposed to the constant wear because of the currents – often rapid – of the Nera river. When the new riverbed stabilized, the need might have been felt to open another arch to guarantee the continuity of passage of the left bank and also to ensure and increased flow of water when the river was seriously flooded. The results of the study of the slope of the viaduct made it possible to put forward a hypothesis intermediary to that calculated by Eng. Riccardi in 1837 (objectively too steep for vehicles) and the one redesigned by Cecchi in 2003, incompatible in relation to Narni and, as to its extension towards the Terni valley and the cave, placed too high. While extracting information from these models, we did not limit our interest to the geometries of the whole work but tried to approach the detail as close as possible and study directly the construction apparatus. As mentioned, already at first visual enquiries we have observed substantial differences between the first and the second span of the bridge: the first rounded arch has a constant intrados, just like the second and the third ones as the ruins and the iconographic appara-

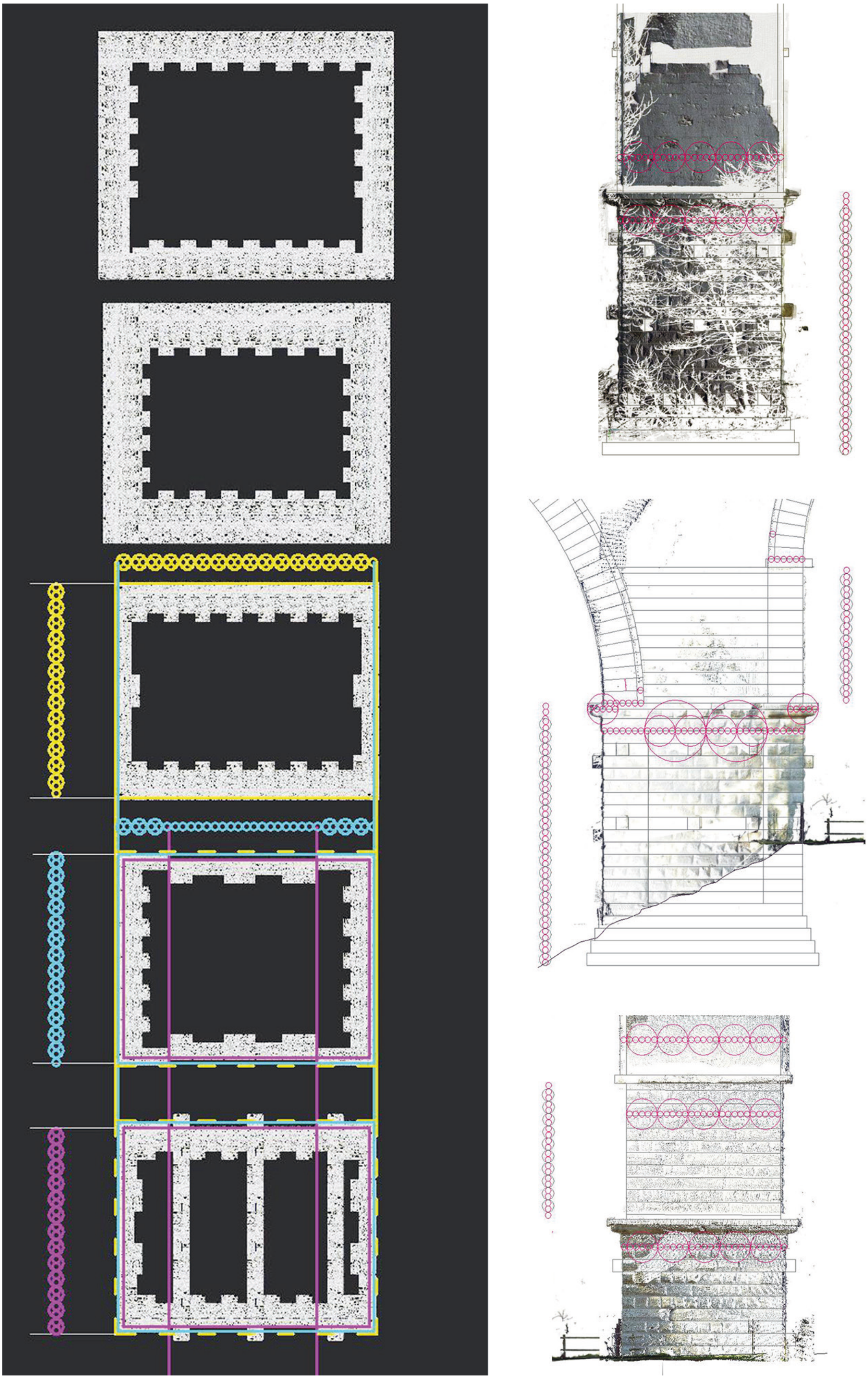


Figure 5. Analysis of ashlars of the first pylon in relation to filars modelled in a parametric environment and a discontinuous model: a) the river part, b) the mountain part, c) the road part.

tus at our disposal seems to reveal. The ruins of the fourth arch are completely different, the arch having been endowed with a non-constant intrados constituted by five reinforcement rings. This construction technique ensures equal structural value while cutting back on materials. This methodology prompted a hypothesis of the fourth arch having been modified in relation to the original design or constructed later than the others. Likewise, the support pylon of this arch has been found different, first of all by the first one - upstream and downstream - has frames and is generally narrower, 9.50 x 7.50 m. The third pylon is regular, has no frames and measures 9.90 x 8.00 m in section.

Also, this factor made us think that the structure was remade at a time later than its construction. Oddly enough, the second pylon has more aspects in common with the third one than with the second one: there are no frames and could have been regarded as regular in section measuring 9.90 x 7.50 m if it were not for some alterations at the base that make it reach the cross-section measurement of 9.90 x 8.00 m. The quoted data seem to support our hypothesis that the last arch was modified in time or was built after the others. Looking for the original form of a bridge with three arches when the first and the third one are reduced and the second one considerably larger, makes one seek a construction motivation that cannot be found in the composition rhythm A-B-A, but that would be functionally compatible with the environment of the bridge. It is not groundless to think, for example, that the river similar at the epoch when the bridge was constructed as it is today, and with the bed so much reduced in width, that it could pass easily through the span of the second arch.

The data acquired with the laser scanner made it possible to obtain not only the main general measures of the ruins of the pylon but also the minute details of masonry equipment. The study of construction equipment did not finish with the analysis of surfaces. Thanks to the condition of the second pylon, broken into three parts after it collapsed, we could have no uncertainties as to its structure and the technique of assembling and fixing stone blocks. So, the bridge is a robust example of rubble masonry with lateral surfaces in opus quadratum, with ashlars and wedges rusticated in local travertine while the toothing between blocks is effected with metal staples and the internal nucleus is made of concrete composed of lime, sand, pebbles and travertine chips. We have deduced from our analyses that there were rigid rules regarding the cutting and assembling blocks of stone. Each part is 2 Roman feet (59.3 cm) tall and they are arranged in the way that alternates the cuts (always in two modules) to obtain a square block 2 x 2 m. The fascia is of variable dimensions, but always conforms to the unit of measure. Evidently this rigidity in assembling stone blocks was respected particularly with the first pylon and not with the third one which was erected later on and is composed of reused blocks, which can be gathered from the signs on the blocks used to raise ones that are completely out of measure with the last pylon (Figure 5).

In order to present the highest possible level of knowledge acquired so far, the decision was made to model the structure of the bridge by means of a parametric modeler, thus creating families that would evince precise characteristics imposed on the basis of rigid geometric and measuring rules identified to date (Figure 6)

The application of this methodology generated a model in the way much similar to the proper construction of the bridge at the building site, creating blocks and filars one by one, all in the optimized way due to the fact that the blocks were adjusted to the imposed binds as well as to the possibility of generating cascading modifications starting with but one unique parametric variation (Figure 7).

The construction principle of the pylon is developed starting from the regular monolithic volume of 33 feet + 1/3 (in Figure 5, the measurement in yellow) equivalent to 9.90 m as measured immediately under the springer of the arch, which we invariably find in the third pylon. From these fundamental measure volumes, multiples of 1/3 of a Roman foot are subtracted. The frame plane (in cyan in Figure 5) is placed at the distance of 1/3 of the upper one while the plane at the back (in magenta in Figure 5) – at the distance of 2/3 from the one preceding it. Thus, we arrive at the minimum measure of 32 feet + 1/3 equivalent to 9.60 m. Finally, there are the basement filars that reach up to 1/3 of the Roman foot in thickness descending to the ground. In view of this evidence, the two pylons at the ends seem less different. Starting from an architectural project based on precise volumes and dimensions, the first pillar changes its volume according to the architectural logics just described, the third remains constant.The

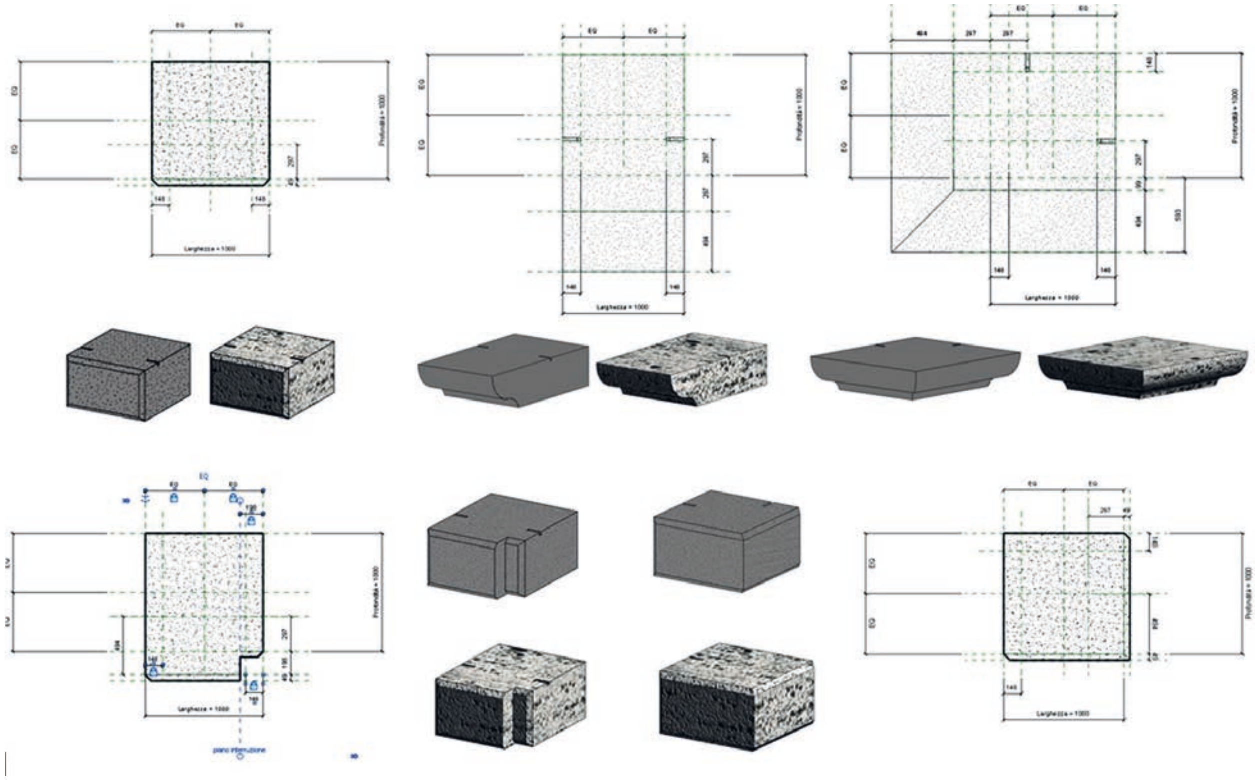


Figure 6. Creation of parametric families to form ashlars.

second is the pylon for which a number of disparate hypotheses were generated since has a constant pedestal at the base which makes us think that it was precisely the basement level. Yet it has been discovered at a certain distance from the springer of the arch that is shorter that the one of the first pylon. This is precisely why so many scholars have supported the hypothesis that springers were misaligned and the arch is not a rounded one. Nevertheless, it can be maintained with high degree of certainty that the arrangement of the blocks is similar to that of the third pylon and that it was erected later on. Moreover, we know that after the bridge had collapsed in 1053, a wooden gangway was built on the stone bridge to make it crossable. Thus, a hypothesis was put forward that when the terrain subsided, the second pylon was adjusted to allow the construction of the temporary wooden bridge. The structure of the pedestal has holes aligned with those of the first pylon, used to fasten the bar of the bow construction. This may lead to the idea that the two pylons were built in the same period, but the blocks are arranged in a completely different way (Figure 8).

It is also worth noting the presence of holes for the wooden provisional works on the right side of the third pylon and on the left abutment. If this technique had been used in the second arch to not engage the wooden works with the river water, it is also possible to think that the same technique could have been used for the construction of the fourth arch, during a period when the water level was much higher. The absence of housing holes in the first and third arches supports the hypothesis that these would have been built on a ground surface that was not submerged at the time (Figure 9).

Results and Conclusions

This study proposes two hypotheses regarding the original shape of the Augustus Bridge: the first one – with four arches, for which the fourth outcome of original construction work established the rhythm of A-B-A-C (where the measures of A and C close to each other); and the second form with only three arches. For both the reconstructions, it has been established that the first and the third arches are identical with respect to the construction technique applied and to their dimensions, which had the advantage having the same ribs used at the worksite.

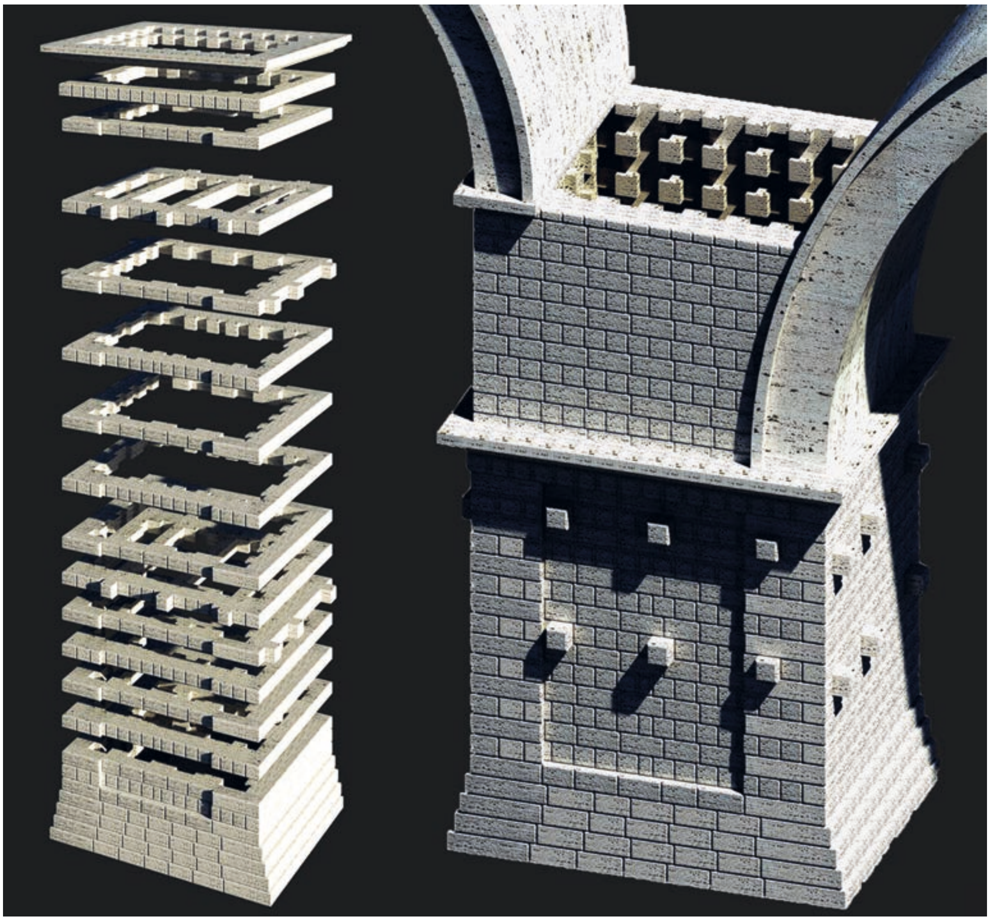


Figure 7. Model construction in a digital building site.

The span of the second arch (the biggest one) can be explained by the necessity to span the river with a narrowed bed. Moreover, the distance between the springer line of the smaller arches and the keystone corresponds to the fundamental measure of the pylons - 33 + 1/3 roman feet. It was also observed that the distance between the springer of the first arch and that of the second one has exactly twice as big as that of the third arch.

The smaller arches are endowed with radial blocks of 3 degrees, as compared with two degrees of the bigger arch. According to our hypothesis, the slanting of the bridge is caused by the unity of the keystones in the first and the second arch and measures exactly 2 degrees in horizontal plane. The keystone of the third arch was not take into consideration in these calculation as it is positioned according to a measure derived from the first one. The hypothesis as to the construction of the bridge is that the two pylons must have been much similar as to their construction. (Figure10)

The present study demonstrates that ruins of and ancient bridge frequently constitute strategic evidence of an environment which can evolve considerably with the passage of time. An ancient bridge, especially when it links two river banks, is often an object difficult to survey because of the specific nature of the environment into which it is immersed. Our research group was especially interested in ancient Roman bridges in order to identify a methodological procedure for the purpose of achieving homogeneous results and ensuring a comparative reading of these structures, keeping in mind their historical, architectonic and geographic differences. The ultimate objective was the analysis, preservation and promotion of cultural heritage starting with the initial design of the work, considering the labour organization at the building site from the beginning until the completion of the work of architecture.

Figure 8. Holes in first and second pylon.

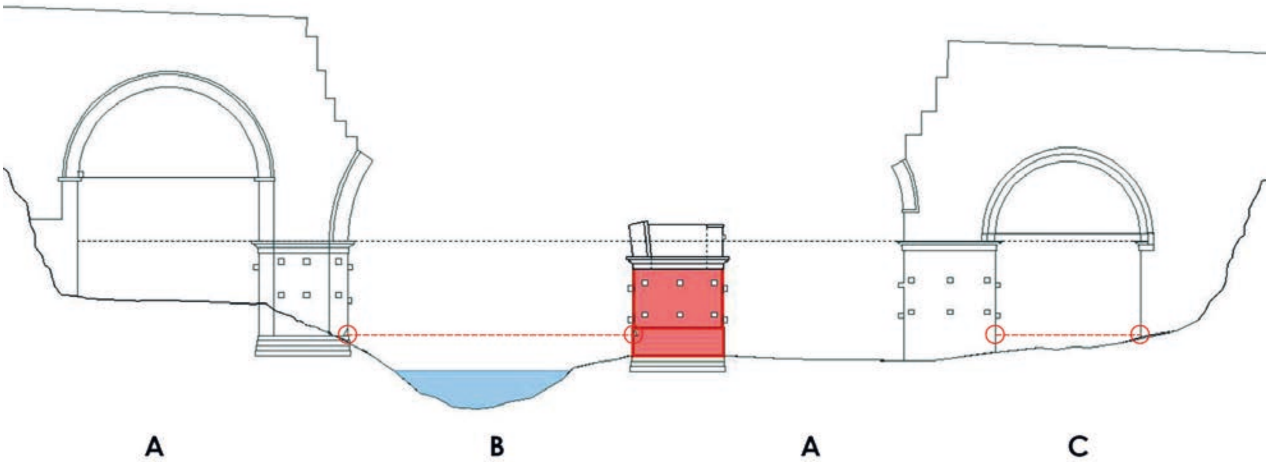


Figure 9. Alignment of holes for fixing wooden ribs demonstrates the corresponding misalignment of the two springers in the second arch.

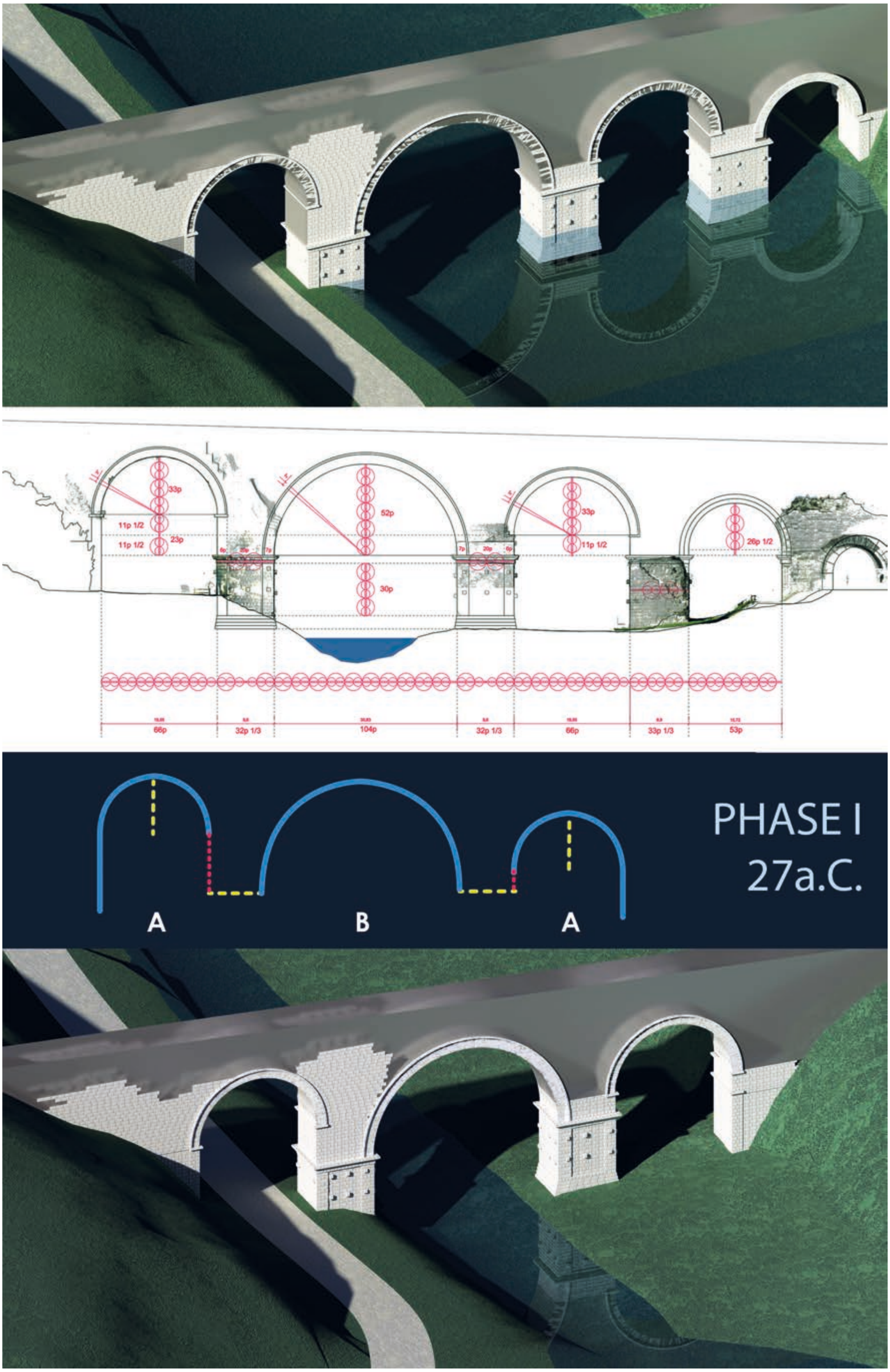


Figure 10. Hypothetical reconstruction using the base point cloud. Proportioning and metric analysis in Roman feet. Original form of with four and three arches.

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Unsettled Settlements: Documenting Site Abandonment and Transformation in Modern Greece

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Abstract

The Deserted Villages Project is a multidisciplinary study of 19th- and 20th-century settlements in Greece. The short period of inhabitation in these settlements presents opportunities to document evidence of site formation, decline, and transition using a variety of methodologies. Two case studies will be presented. In the mountains of Phocis, villages founded in the mid-19th century and burned by the Germans during World War II are documented through traditional and GPS survey, UAV based aerial photography, close range photogrammetry, and the collection of oral histories. On the coast of Macedonia, a Cold War settlement for the Voice of America radio station near Kavala is documented through terrestrial photography, GIS, and video. The settlement, occupied from 1972 to 2006, presents a short-lived example of American domestic architecture transplanted into the landscape of rural Greece.

Keywords: GIS, photogrammetry, historical archaeology, architecture

Introduction

The Greek landscape has played a special role in the Western imagination as embodying idyllic ideals unadulterated by modernity. Created by early travelers and archaeologists, this notion is perpetuated by tourism, which promotes aspects of Greek culture as unchanging and rooted in the landscape. The violent history of Modern Greece, however, has disrupted lived continuities between the present and the past. Beginning in the 1970s, archaeological field surveys mapped the nuances of the cultural landscape through the collection of surface pottery and the modeling of temporal and spatial change. Settlement patterns have shifted radically in response to global and local forces. A more dynamic model of the Greek landscape has been corroborated by ethnoarchaeological research carried out along with surface collections (Forbes 2007; Pavlides and Sutton 1995; Sutton 1994). Susan Sutton (1988) traced the fluctuating demographics of rural life from the 16th century to the present, noting that village foundations, demographic decline, and related population movements were frequently associated with changing political realities and villagers' participation in local, regional, and global economies. The modern village of the 16th to the 20th centuries is, therefore, a fragile spatial entity defined by the mobility of populations and capital rather than a static repository of ancient values. Migration and depopulation remain core components of life in the Greek countryside. The settlement pattern of Greece became increasingly ephemeral as a result of economic bankruptcies (1893, 1929, 2009), wars with its neighbours (1897, 1912-13), World Wars (1919-22, 1940-44), civil war (1946-49), and dictatorships (1925-26, 1936-41, 1967-74). Although escalated during the 20th century, migration within and beyond the national borders was a common and

Figure 1. Map showing the location of Aigition, Kavala, and Distomo.

vital part of this process, producing a landscape of perpetual abandonment and resettlement (Kourelis and Caraher 2010).

Although scholarship has increasingly accepted this dynamic model of the Greek landscape, little attention has been placed on how such change has affected the architectural fabric of settlements. Even less attention has been given to the archaeology of Greece's most recent past. The blossoming field of an archaeology of the contemporary world has used the notion of supermodernity to characterize the heightened destruction occurring globally between World War I and the present (González-Ruibal 2008: 247). Two case studies in Central and Northern Greece provide a fertile arena to investigate the effects of supermodernity through the archaeological study of domestic architecture (Figure 1). The village of Aigition, Phocis is a traditional Greek village founded in the mid-19th century and sustained by remittances sent back from the United States in the early 20th century. In 1943, the village was burned by the Axis Powers and its residents were interned in a concentration camp in Athens. At the end of World War II, the population resettled in Aigition's ruins. Thirty years later, the village was abandoned as its residents moved away to Athens or more connected places. The Voice of America (VOA) station in Kavala, Macedonia was an American army base transmitting propaganda to Eastern Europe. Its civilian staff were housed in a settlement built to replicate an American suburb. In 2006, this American settlement was abandoned. Although physically and conceptually unrelated, the two sites were the research subjects of the Deserted Village Project, an undergraduate field school that brought together Greek and American students. Both Phocis and Macedonia are regions that experienced supermodernity's extreme unsettlement. The studies of Aigition and VOA presented instructive challenges on how to map and interpret the materialities of crises in the recent past grafted on the physical remains of rural settlements. The following sections briefly discuss methods used in the study of Aigition and VOA.

Aigition

Since 2010, an international team of scholars has investigated the diverse natural and man-made landscape surrounding the modern village of Lidoriki in the prefecture of Phokis, central Greece (Figure 2) (Brenningmeyer, Kourelis, & Katsaros 2016). At the center of the study area is the artificial Mornos reservoir, which dominates the region's topography. In the early 1970's the Greek Water Supply Company (EEY) created the reservoir to meet the growing water needs of the city of Athens (Ananiadou-Tzimopoulou and Nana 2015: 76; Kaika 2005: 136). Its construction flooded archaeological sites and cut off historic transportation and communication routes that once connected small villages in the surrounding countryside. Ancient Kallion (Kallipolis) was among the most important ancient sites impacted by the flooding; rescue operations were carried out by an international team of archaeologists who recorded the site before its inundation (Herbert and Kase 1977; Laffineur 1977; Laffineur 1978; Laffineur 1979; Laffineur 1980; Themelis 1979). Modern houses and settlements located along the Mornos valley were likewise submerged within the lake. Communities located in the mountains surrounding the lake found themselves isolated by the reservoir's construction. The village of Aigition, located on a mountain ridge

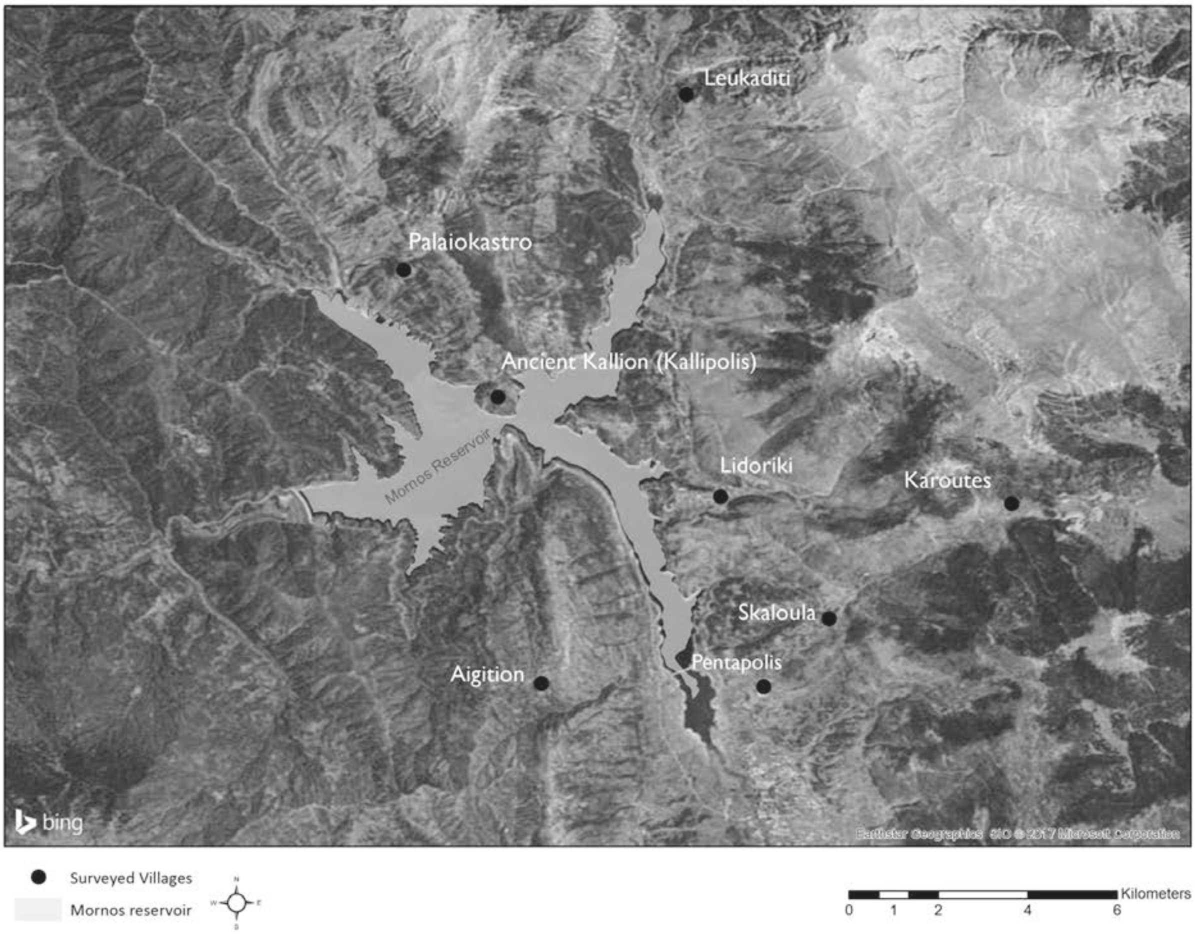

Figure 2. Map of the project area surrounding the Mornos reservoir.

west of Lidoriki, was among the settlements impacted. The process of decline and abandonment that began in the 1940s solidified in the 1960s as residents migrated to villages closer to primary transportation routes. Aigition has been a focus of our investigations from the beginning of the project.

The history of Aigition can be traced to the 19th century when the village was known by the name Strouza. This name has been identified in Ottoman registers from the late 15th and 16th centuries, but there is no evidence of structures built before mid-19th century (Doorn 2009: 200). The notion of an earlier village located at Palaiokastro survives in the oral histories. The physical evidence at Aigition suggests that the foundation of the settlement is contemporary with the dedication of the village church in 1852 (marked by an inscription on the church's east apse). This date corresponds with the period of general agricultural prosperity that followed the establishment of the Modern Greek state in 1832, when fertile lands belonging to Ottoman feudal lords were passed to Greek owners (Frangakis-Syrett and Wagstaff 1992). Aigition likely developed through the gradual nucleation of small pastoral settlements before formally establishing itself as a village through the dedication of the church. Work by the Archaeological Survey School of Holland (1989: 239) underscored the historic importance of pastoral economies in the area surrounding the village, noting that significant environmental changes took place in this area during the 19th century as woodlands were deforested and converted into shrubbed pasture lands.

The history of Aigition after its foundation follows many of the patterns noted elsewhere in Greece. The village, along with the rest of the region, experienced a demographic boom in the 1870s (Asdrachas 1979). By 1893, a phase of slow decline brought on by Greece's financial collapse led to emigration. Members of the village were among the quarter million Greeks that immigrated to the United States. Local informants identified houses in Aigition that were constructed using remittances sent from the United

States. Two donor inscriptions on a house (1915) and the school (1909) mark immigrant donors that can be traced-through the records of Ellis Island-to Madison, Wisconsin. A sizeable diaspora community from Aigition settled in Chicago. The Balkan Wars, World War I, and World War II further transformed the village. The most dramatic episode occurred on July 23, 1943, when the German army burned the village and sent its residents to a concentration camp in Athens. The central village of Lidoriki was also burned on August 29, 1944. Further east, the mass execution and burning of Distomo (Figure 1) received international attention (Life 1944). The residents of Aigition returned after the war and resettled the ruined village. In 1950, some of the residents moved to the new village of Pentapolis located in the plains along modern roads and infrastructure. Census records indicate a significant population decline between 1951 (324 residents) and 1961 (120 residents). By 1971 the census records 0 full time residents remaining (Stamatelatos and Vamva-Stamatelatou 2001: 432). The history of the village from 1971 to the present is one of gradual decline. Some buildings in Aigition have been converted to temporary seasonal residences (kalivia). A small number of buildings has been renovated by past residents or their descendants, while the vast majority are in a state of disrepair and ruin. The documentation of these buildings provides a window into the processes of abandonment and site formation, while providing a historical record of unique regional architectural traditions exemplified in the construction practices of the builders.

Project Data

While the village of Aigition had not been systematically studied prior to our investigations, historic documents and published regional survey reports record regional topographies and lifeways. Early travellers describe the region's late 19th century geography within travellers' accounts and tourist guidebooks (Bazin 1864; Murray 1900: 650; Woodhouse 1897). Historic maps illustrate the principal settlements in the region along with transportation routes. The Dépôt de la Guerre produced the most detailed of these in 1852 at a scale of 1:200,000. It provides a remarkably detailed record of routes and settlements

Figure 3. Project team conducting interviews in Aigition.

and was the earliest to identify Aigition's position on regional transportation networks. More recent studies provide a foundation for interpreting the site within its regional context. During 1980s and 1990s, the Aetolian Studies Project of the Netherlands Institute in Athens surveyed a large area that extended from Mount Giona in the east to the Achelous River in the west (Bommeljé 2009; Bommeljé and Doorn 1996; Bommeljé et al. 1987). While their study did not publish details about Aigition, their research area encompassed the village, and their team used the village as a base during their survey of the surrounding region. Their published survey data and maps of Aetolia were incorporated into our project GIS. Maps at 1:50,000 scale, compiled by the Hellenic Military Geographic Service (HMGS) in 1971, 1975, and 1988, provide more recent details about the topography immediately before and just after the flooding of the valley. Two sets of declassified CORONA KH-4A satellite images acquired July 26, 1965 and February 1, 1968 provide further coverage of the area and illustrate patterns of land use in the valley before the dam's construction. Taken together, the historic datasets informed our understanding of Aigition's place within the regional history.

The investigation of Aigition involved oral interviews, including the last resident of the village Demetrios Kafritsas (1941-2017), who recounted the burning of the village and its reoccupation in the 1940s (Figure 3). Our collaborator Sophia Klossa has been instrumental in collecting oral histories, as well as founding and curating the Lidoriki Folklore Museum, which opened its doors in 2017. The Deserted Village Project created a photographic inventory of the collections and created 3D photogrammetric models of prominent objects for presentation. Informants from Lidoriki and other nearby villages provided additional accounts of Aigition and the surrounding region. Research on social media has also allowed us to discover and interview émigrés that have settled in America and Europe.

In 2010 initial survey work began at the village. Traditional land survey with a total station and manual architectural survey were coupled with preliminary aerial reconnaissance using balloon aerial photography (BAP), pole aerial photography (PAP), and kite aerial photography (KAP). The aerial reconnaissance relied on techniques applied by team members on the island of Karpathos and in the Peloponnese (Nelson et al. 2015). BAP and KAP photography used small Canon S90 and S110 automatic cameras suspended from a 3.3 m3 helikite or a range of kites tailored to specific wind characteristics. PAP photography used a similar camera elevated on a 9 m carp pole. Scripts written using the Canon Hack Development Kit (CHDK) and Stereo Data Maker (SDM) automated camera capture during flight. A video transmitter attached to the camera allowed the surveyors to track the camera frame remotely. Architects from the National Technical University of Athens developed measured plans of a handful of buildings within the village as well as nearby mills, bridges, and decorative components of notable structures. By 2014, the project added an Unmanned Aerial Vehicle (UAV) to the survey toolkit to more efficiently document the village and its topography. The process and preliminary results of this work were published in Brenningmeyer et al. (2016). The results of this work provided a detailed orthophoto and map of the site and its architecture. This information was further situated within regional data extracted from previous surveys, traveller's accounts, and historic maps and imagery.

Methodology: Photogrammetric Architectural Survey

During the final two field seasons (2015 and 2016), the project focused on developing a complete catalogue of Aigition's architecture. While architects had developed hand drafted plans of notable buildings during previous seasons, greater emphasis was placed on documenting the full range of structures represented at the site in preparation for a study season and publication. Structure from Motion (SfM) and Dense Surface Reconstructions were implemented for the rapid collection and reconstruction of architecture in the village. SfM is an automated method for estimating three-dimensional coordinates from overlapping photographs that developed in the field of computer vision research (for brief overviews of SfM, see Carrivick et al. 2016; James and Robson 2012). Like traditional photogrammetry, it relies on overlapping photographs to generate measured reconstructions. While SfM shares some similarities with traditional photogrammetry, the process and requirements differ. Traditional photogrammetry requires a calibrated camera with a well-defined collection process to ensure at least 60 percent forward overlap and 30 percent side overlap in every image. SfM by contrast is designed to work with unordered photographs taken with cameras that may vary in terms of their lens characteristics (see for example Carravick et al. 2016; Snavely et al. 2006; Snavely et al. 2008). SfM software estimates the interior and exterior orientation of the camera while identifying matching features across processed photographs. While the quality of the lens and camera are still limiting factors in the quality of the final models, SfM offers flexibility that is not typical to traditional photogrammetric projects. The output of SfM processing are a sparse point cloud and reconstructed camera positions. These may be used on their own or (more typically) become inputs for software that applies algorithms to produce a dense surface reconstruction in the form of a dense point cloud and/or mesh (Carrivick et al. 2016: 50). While we experimented with a variety of platforms during the course of the project, we currently use Agisoft PhotoScan Professional for our reconstructions. PhotoScan provides a simple workflow for model construction. The program, however, does not currently publish the algorithms used for their SfM and dense surface reconstructions. Notes on their website suggest that Multi-View Stereo (MVS) and "pair-wise depth map computation" are used for dense surface reconstructions (Semyonov 2011; see also Dall'Asta and Roncella 2014:190).

Photographic and video inputs were used to develop architectural reconstructions. The collection and processing of these inputs present two different approaches for rapid survey of architecture. In 2015, students and researchers collected overlapping pho-

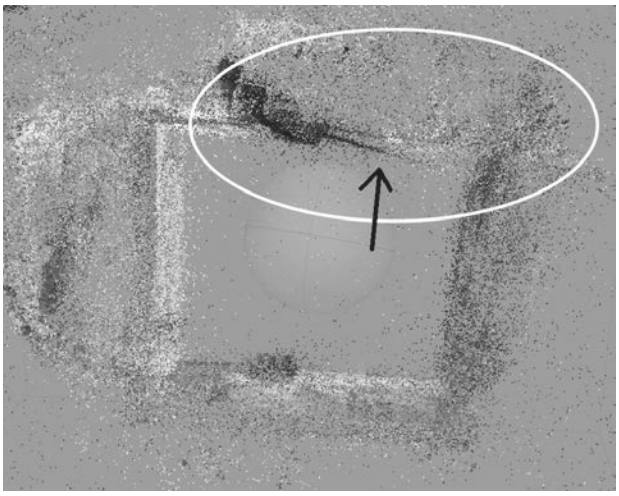

Figure 4a. Sparse point cloud of Building 12 from Aigition showing poor alignment at left caused by small baseline distances.

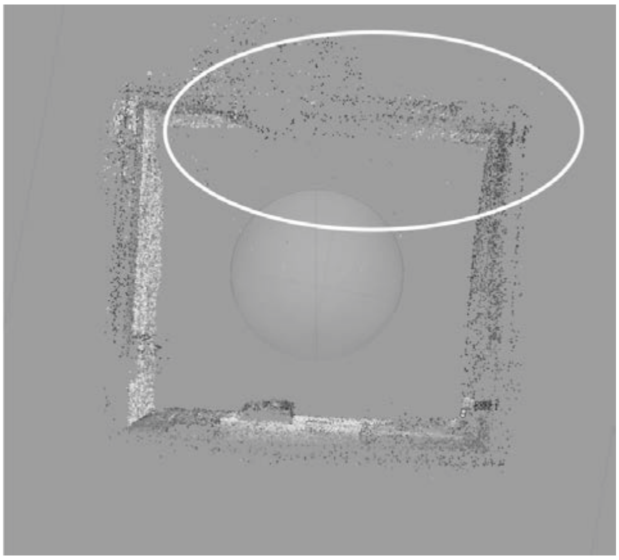

Figure 4b. Building 12 with improved alignment using refined selection of photos with improved baseline distances.

tographs of building exteriors using DSLR cameras as part of the 3D reconstruction effort, often taking 500 or more photographs per house. Surveyors used Nikon D5000 and D750 cameras for much of the collection with a few houses surveyed with compact cameras (Canon Powershot G12, and S110). Frame numbers were associated with building IDs noted on preliminary printed maps of the village. These frame numbers were later associated with corresponding buildings within the developing project GIS. Surveyors carefully positioned cameras to ensure at least 60 percent overlap between frames. Care was taken to capture transitions along corners and between building exteriors and interiors. In many cases, camera set-

Figure 5. Reconstructed model of Building 12 from Aigition, created using iPad videos.

up was time consuming. The village rests on the top and sides of two broad ridges separated by a narrow draw. Buildings lie along the edge and top of slopes with fallen building debris and stones spread across an uneven ground. Scrub vegetation, in the form of Kermes Oak and various xerophile herbs and grasses further obscured many buildings and increased the difficulty of accessing some areas. Using this photographic collection process, our crew members averaged approximately 1-2 buildings per day. The speed of the photographic collection severely limited the number of buildings that we were able to document during the 2015 season. In some instances, surveyors collected enough photographs to reconstruct only one or two sides of a building.

In 2016, we returned to Aigition to begin our final season at the site. A decision was made to forego broad DSLR photographic collection in favour of video, which would provide contextual information for reviewing architectural details during the study season. We also believed that the use of video would speed the collection of image data for our model reconstructions. DSLR cameras were reserved for documenting architectural details and images for publication. 10.5” iPad Pros were used for the video collection. The decision to use the iPad Pro was pragmatic. The iPad is a device provided to all faculty and students from one of the survey’s participating institutions. The devices, therefore, were readily available and students involved in the data collection were familiar with their use and could rapidly begin the video survey. The iPads also facilitated GIS data entry and update using a mobile GIS that was installed on each device. iGIS, a mobile GIS app that integrates with Apple devices, was used as our mobile GIS platform. iGIS has options for form creation, which provided opportunities for quality control while entering data in the field. An orthophoto, produced using the UAV data collected during previous seasons, provided a high-resolution backdrop for the mobile GIS and simplified identification of buildings by student surveyors. Students were able to navigate to specific structures, rapidly collect detailed videos of the exteriors and interiors, and enter collection data directly into the mobile GIS, which was later synced with the project GIS maintained within ESRI's ArcMap program. As with the previous DSLR photographic collection, surveyors captured video footage of each building in regular swaths that extended from the bottom to top of house walls. The surveyors ensured that vertical swaths overlapped by at least 30 percent on each side. The number of buildings surveyed in this way increased from 1-2 to 10-11 per day.

The videos collected during the 2016 field season were post processed with FFmpeg, an audio/video encoding and decoding tool, to extract frames for model reconstructions. Similar workflows have been discussed by Teo (2015) and Block-Berlitz et al. (2015). Approximately three frames were exported as .jpg images for each second of recorded video. These images were input into Agisoft PhotoScan with blurry or redundant images removed from the image set. While the videos provided excellent overlap between frames, the exported images sometimes overlapped too much to generate accurate measurements. In SfM applications, as with traditional photogrammetry, measurement uncertainty increases when using photographic pairs with small baseline distances. Models that are derived from images with small baseline distances may have offsets in the resulting point clouds and points that "noticeably deviate from the object surface" (Agisoft 2017: 65).

Figure 4a presents such a situation. The image presents a sparse point cloud of a house from Aigition, shown here in plan view. As can be seen in this image, points located along the front of the building (circled in Figure 4a) are significantly offset from the surface of the structure. A line of points highlighted by an arrow, deviates from the angle of the house facade. The misalignment of these points resulted from a poor alignment of images with small baseline distances. These images were manually selected and removed in Figure 4b. The sparse point cloud was further refined through an iterative process of point selection and deletion. Points falling outside specified tolerances for reprojection error, reconstruction uncertainty, image count, and projection accuracy were selected and removed from the point cloud. After each iteration a camera optimization was run to improve camera alignment. While this process improved the models, the process of manual selection and removal of images was time consuming and future work will explore automated approaches for the identification of images used in reconstructions.

Results

In most cases, the frames extracted from the iPad videos provided excellent overlap and continuity for construction of 3D models and most buildings had sufficient coverage and image overlap to produce high definition point clouds. The reconstructed model shown in Figure 5 presents one example of the output of this video derived model construction. Initial comparisons of the models generated from video frames with those created from the DSLR photographs indicate difference in the detail captured using the two techniques. The resolution of the iPad video is lower than that of the DSLR photographs and the texture maps covering the surface of the models preserve this difference. Figures 6 and 7 present two models of the same wall. The DSLR based model (Figure 6) preserves the tool marks and construction details along the quoins. These features are obscured in the video derived model (Figure 7).

While we did not compare the point clouds, it is possible that differences in the accuracy of the two models are also present. The differences in accuracy, however, are not evident upon visual examination. For our purposes, the ability to rapidly survey and document the site within a short span of time outweighed the reduction in resolution associated with the video capture method described above. The models generated from the survey have been uploaded for display within Sketchfab and the project's web-GIS (Figure 8).

In future work we would like to compare differences between the accuracy and resolution of models produced with iPad video to models produced from video captured using other hardware. The videos taken during the survey were 1080p HD video at 30 frames per second (fps). The iPad is capable of col-

Figure 6. Screenshot showing reconstructed wall of Building 84 generated from DSLR photographs.

Figure 7. Screenshot showing reconstructed wall of Building 84 generated from frames extracted from iPad videos.

Figure 8. Screenshot of Deserted Villages Project's WebGIS.

lecting 1080p at 60 fps and 4k video at 30 fps. These options were not used but would likely have resulted in better quality frames and more accurate reconstructions.

Voice of America, Kavala Station

During the 2016 field season, the project began exploration of a relic of the Cold War, the Voice of America relay station near Kavala, Greece. The Voice of America (VOA) was a shortwave radio station that began to transmit against Nazi propaganda in 1942. During the Cold War, it became a media instrument to combat Soviet propaganda. Greece's proximity to the eastern bloc positioned it as the ideal centre for transmission. In 1952, VOA established a relay station based on a navy ship off the coast of Rhodes. The permanent station at Kavala was built in 1972 as one of the last major capital investments of VOA (Heil 2003: 115). It included extensive technical facilities and antennas that broadcast globally between 1972 and 2006. In order to meet personnel needs of highly qualified civilian broadcasters and technicians, the VOA station required adequate housing for families coming from the United States. Although it operated as a military base, the VOA housing resembles a mid-century modern American suburban subdivision with ranch-style private family dwellings (Figure 9). The houses have dramatic sloping roofs originating in the progressive language of American domestic architecture in the 1960s (Lane 2015). The transplanted VOA American development in Greece raises interesting questions over the transmission of American suburban ideals through architecture. The station was turned over to the Greek government in 2006 and much of the transmission equipment has been dismantled, sold, recycled, or looted. When the VOA closed, the Greek government hoped to reuse the equipment and asked the U.S. Army not to destroy the base, as was protocol. The station was never reused. The houses, like the abandoned villages of the Mornos Reservoir, are slowly becoming ruins.

In the last decade, the new field of Cold War archaeology has steadily grown. Field research typically covers nuclear test sites in the U.S. (Beck 2002; Hanson 2016), radial defence systems (Whorton 2002), missile sites in Cuba (Buström 2009), installations in the Soviet Union (Fowler 2008), frontier zones in Czechoslovakia (Rak, Funk, and Starková 2016) and Ethiopia (González-Ruibal 2006). The VOA station in Kavala presents an interesting counterpoint to this scholarship in targeting residential rather than defensive material culture. The VOA station was located within NATO's sphere of influence and projected immaterial radio waves to the Soviet bloc. Its residential cul-de-sac is a surreal implantation of an American suburban dream in an otherwise Greek landscape. The houses are strikingly different from contemporary housing in Greece in their central air-conditioning systems, their sprawling horizontality, and their irregular placement around driveways. Interviews with the last Greek foreman of the VOA revealed the name of the firm that designed the enclave, Holmes & Narver, Inc., from Orange, California.

Figure 9. House documented at the VOA Relay Station, Kavala, Greece.

Methodology

The site's typological regularity coupled with the existence of construction blueprints obviated the need for an aerial survey of the site. Documentation, instead, focused on recording each individual house and the grounds that surround it. As in the case of the 2015 Aigition survey, we used video recording to document house interiors and exteriors. iGIS was used as our mobile GIS platform. iPhones were used for much of the GIS update with iGIS using the onboard GPS to geotag photos of houses, pump stations and other structures that document the current condition of the settlement. Each photograph was automatically embedded within the mobile GIS and titled using a naming scheme that concatenated the GIS feature class, house ID, and photo number. While the

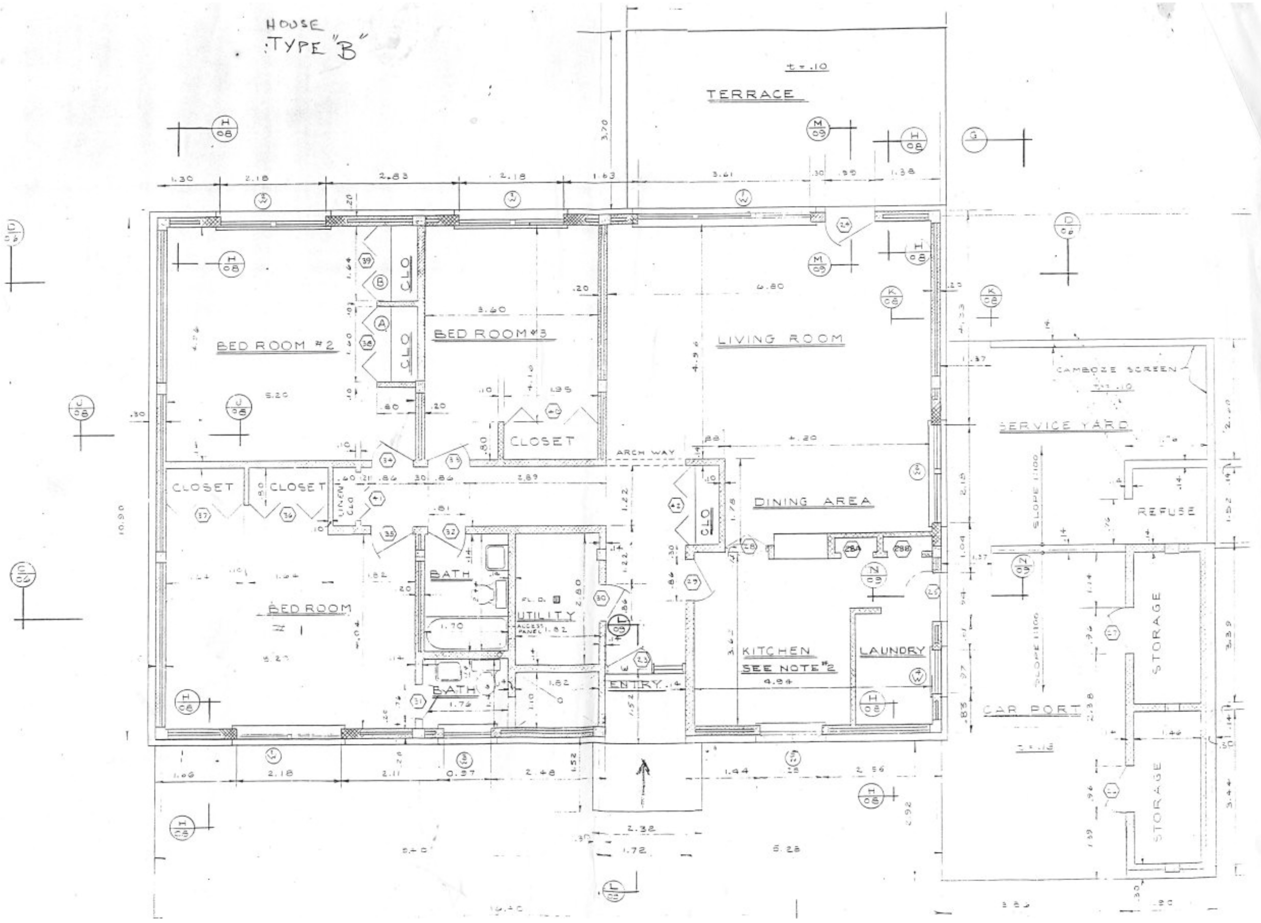

Figure 10. House plan recovered from the VOA Relay Station, Kavala, Greece.

iPhone's GPS had limited accuracy, it was sufficient for basic location of features on facility plans. A satellite image, loaded into the background of the mobile GIS, provided contextual information for students as they navigated the site. Using this system, students were able to quickly and systematically document and photograph features.

Still photographs also were taken of each house, focusing on the relative chronology of building elements. Such internal variations could periodize changes in added fixtures (such as lighting, shutters, window frames) in the 30-year horizon of the site's inhabitation. The frame numbers for these photographs were entered into the mobile GIS and attached to the corresponding house within the GIS. While most houses had been emptied by their American inhabitants, rare elements that were left behind were noted by the surveyors. These included exercise equipment, office furniture, video tapes, mechanical manuals, and correspondence. Finally, a record was made of evidence of post-abandonment inhabitation that illustrates squatting or semi-official residence post-2006.

Results

Our investigations at VOA are in the early stages with work focusing primarily on data collection activities. The remains of the VOA suburb are pristine enough to provide good evidence for typologies of abandonment and post-abandonment processes. Logbooks, elementary school materials, mail, and other materials left behind by the final residents document the final history of the site. Architectural plans, digitized as AutoCAD dwg files by Greek workers in 2003 (Figure 10), complement our site survey and preserve the original house designs and facility plans. This information, together with surveyed data, provides the core of our developing project GIS (maintained in ESRI's ArcMap). Greeks who worked on the station were interviewed during the 2016 field season, providing a window into life at the site both during and after its American occupation. We hope to interview other individuals (especially the American staff) that lived and worked at the station as the project progresses.

Summary

Ancient monuments and sites dominate archaeological practices in Greece. As a country dominated by national narratives of a glorious classical heritage, the archaeology of the recent past presents unique methodological and interpretive challenges. The progressive above ground ruination of historic buildings necessitates innovative and efficient documentation of three-dimensional structures and spaces. The projects presented in this paper, illustrate examples of two diverging approaches for investigating the recent past. At Aigition, aerial and terrestrial survey documented traditional architecture within a rural landscape. Detailed hand drawn plans provided a direct observation of construction methods and architectural details, but this process was time consuming and significantly limited the number of buildings that could be documented in a field season. A hybrid approach involving hand drafted plans of notable buildings and photogrammetric documentation of all structures allowed the project to rapidly survey the village. Similar approaches have been implemented for building archaeology elsewhere (e.g., De Vos 2017). The use of video as a documentation tool and as a medium for capturing data for architectural model generation significantly increased the speed and thoroughness of our survey process. The use of iPads for data collection was sufficient for model creation but at a diminished quality when compared with DSLR based models. The approach presented worked well within the diverse architecture of the rural location. A slightly different approach was implemented at the VOA site. Unlike the houses at Aigition, the VOA buildings were constructed using standardized architectural plans. The base maintained records of these buildings through 2006 when the site was abandoned. Building plans, converted to AutoCAD dwg files, maintain a record of mechanical and architectural modifications at the site. Within this context, photogrammetric and hand drawn plans were less vital to our documentation process. Videos documented interior and exterior spaces and photographs captured artifacts throughout the built spaces. If needed these could be used to develop photogrammetric models of features or buildings. The existing CAD plans also provide a foundation for model construction. In both projects, a small mobile GIS app (iGIS) allowed students and surveyors to rapidly enter and update data in the field using their iPads or iPhones.

The approaches applied in the two surveys illustrate the use of low-cost tools for rapid survey and data acquisition and update. Our work emphasizes student involvement in the process of research and the projects described provide both an avenue for exploring and documenting the past and a pedagogical environment for involving students in the process of applying technological solutions to the study of historical sites. The study of Aigition is part of a broader and ongoing examination of early modern settlements and the architectural history of the surrounding region. The investigation of the Kavala VOA settlement is in the early stages of study and we anticipate expanding our investigation and student involvement as our research progresses. The examination of settlements bridges the worlds of ethnographic study, historic archaeology, and the archaeology of the contemporary world. We look forward to the process of continuing our investigations of these sites in the coming years.

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Representing Intangible Heritage: Questions Concerning Method

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Abstract

The research explores issues concerning the relation between text and images – an interesting field of enquiry little explored to date – involving archaeological heritage that has not survived and is therefore based on descriptions of artefacts and sites. Nowadays, this heritage can exist again thanks to digital technologies (relational databases) and methodologies (conceptual modelling) that allow the construction of 2D and 3D models. Studied here are the relations between the text and conceptual categories, between description and classification of objects in order to understand how all words and terms influence the results of interpretation and interaction between different profiles in the construction of models. In this context digital methodologies are discussed to assess the actual state of archaeological information systems and reflect upon possible future directions.

Keywords: intangible archaeological heritage, survey, 3D/2D/1D models, digital archive, Pyrgi

Introduction

The relations between literature and figurative arts have for centuries been objects of inquiry which resulted in theories and axioms applied in different contexts and different epochs. Even today the study of the dynamics between the text and the image is an interesting field that runs across different disciplines that investigate human endeavour. Many humanistic disciplines, such as philosophy, aesthetics, literature and history, have always used the text as the instrument for describing models. Ancient rhetoric applies the term ἔκφρασις (*ekphrasis*) to the verbal procedure that transforms the person that reads or listens into a spectator who creates a complex vision of an object, a person, a place or an event, having first decomposed it into articulated elements. Nowadays the term ekphrasis is most usually employed to *signify a text that represents or evokes a visual work of art* (Elsner 2002; Webb 1999; Zanker 2003), emphasizing the relation of subordination of the text to the image and evoking its relations with the visual nature of art. In spite of the ancient origin of this relationship, the debate on the interchangeability between literature and models – understood as a synthesis of data that allow one to visualize an object in space, is even more topical. Interaction between various disciplines puts in direct contact diverse aspects and dimensions of the cultural experience, allowing one to consider each work of art as a composite[1] (Mitchell 1986) and to study the relations between other works of art through the relationship between the text and the image.

The description of archaeological architecture emerged as a privileged sector that concretized the specialization of the term *ekphrasis*. The present study is an enquiry into these relations in the field of

1 The image/text problem is not just something constructed between the arts, the media or different form of representation, but an avoidable issue within all the individual arts and media. All arts are composite arts (both text and image); all media are mixed media, combining different codes, discursive conventions, channels, sensory and cognitive models.

archaeological heritage. In many cases, to comprehend such a number of elements, it is necessary, first of all, to study the existing documentation, in most cases almost exclusively textual. Nowadays quite a lot of archaeological heritage is based on descriptions of objects and places while communicating information is more and more linked to the construction of 3D/2D models enhanced by the development of information and communication technologies.

The construction of such models is especially complicated when their elements no longer exist and when their documentation is solely of the descriptive type - completely devoid of any images or drawings. Thus, it becomes interesting to enquire into the problem how the representation of an archaeological artefact ought to correspond to what is described as well as try to find out to what extent all words and terms used insert the interpretation and interaction between different profiles into 2D/3D model construction. The objects of analyses are the relations existing between the text and conceptual categories, description and classification of objects, addressing the problem of representation of artefacts that are only described. The textual data at the point of departure - while recognizing the essential role of the word - made it possible to translate the text into a model taking advantage of Information Technology tools and techniques for digital modelling and representation.

The text is mainly linked to interpretations of the subjective type when each interpreter refers to his or her own imagination through an adequate use of visual particulars, which is connected to the knowledge everyone has about the object in question. The models emerge as the visual extension of what is described through a character perceived immediately when passing from the verbal sphere into the figurative one. The main focus rests on the transition from the documentation constituted by models 2D/1D[2] towards cataloguing structured into semantic categories of 3D/2D/1D models. Such a classification makes it possible to archive all information and makes for their objectification determining as it does the identity of complex objects whose qualities can be subject to critical assessments (Ippolito and Attenni 2016).

2 Definition of 1D models indicates all the textual, numerical and alphanumerical data, which describe the object and make it possible to define 3D/2D models in virtual space.

Background

The great amount of information that archaeological heritage conveys imposes the necessity of a dialogue between various phases capable of being documented and of spreading information related to acquisition, virtualization, and data communication. Nowadays, the relation between archaeological research and informatization represents one of the most popular fields of research while the definition of potentiality and criticity of informatics system constitutes the most advanced point in the theoretical and methodological debates concerning these subjects. The practice of utilizing such systems has almost become a standard, as relates to the digitalization of documentation obtained from archivist research and excavations at archaeological sites, to the knowledge and documentation acquired thanks to the most advanced non-contact surveying techniques, as well as to the construction of models of archaeological elements on the grand, medium and small scales (Bianchini, Inglese, & Ippolito 2016).

The extraction (production) of the archaeological datum in whatever form it appears requires total transparency. Only then can it serve as the basis for studies and research and be subject to verification. The concept of data transparency is strictly linked to its properties, both quantitative (physical parameters, coordinates, position, geometry) and qualitative (contingent and permanent properties and formal aspects visible *in concreto* in a determined reality). Data measurability nowadays must derive from digital documentation related to non-contact surveying campaigns as well as to the successively carried out operations that serve the construction of 3D/2D models. It offers an important convergence point between architecture and archaeology - not only for strictly practical reasons but also for the theoretical and methodological point of view, thus directing the surveying theory towards the neo-processualistic) approach. Within this approach the quantitative aspect[3] plays the central role in data elaboration (Cowgill 1977, 1989) and becomes successively structured with the nascence of relational databases, all with

3 This approach is based on statistical methods proposed in the 1960s by Albert Spaulding at the very same time when database organized along hierarchical schemes were being developed, all the time remaining within the ambience of linear database.

the objective to construct a strongly particularized (Valenti 2012) picture of general knowledge. However, the development of informatics technologies certainly offers more flexible modes of managing and questioning complex data, when the user has to be able to define methods of accessing, manipulating, representing, and archiving the same data (Valenti 2015). Moreover, and this is the most important, he/she has to be able to validate (or to contradict!) the elementary quantity elaborated (Bentkowska-Kafel et al. 2010; Koutsoudis et al. 2015).

Within this framework of reference digital models of archaeological data - which approach closer and closer the work of the architect, no longer exist as simple hypotheses but as "articulated and dynamic constructions that must be capable of corresponding (responding) to the richness of the elements that constitute the integral part of the context" (Bietti Sestieri 2000). Elaborating such models becomes, then, one of the principal objectives to pursue the path leading to the knowledge of archaeological settings with their intrinsic historical stratifications and structural characteristics. It seems understandable now why the application of computer (informatics) methodologies have recently become fully ingrained in the ways archaeological data are acquired, archived, promulgated and interrelated (Valenti 2000).

We need, then, to understand how technology influences and is influenced by the methodology of archaeology as well as grasp the quality of the relation between technology and methodology when the matter concerns the knowledge (cognition) of complex contexts. In the study of realities that disappeared almost totally, there always re-emerges the question of its the relation with computer (informatics) technologies. In particular, one of the principal aspects to be considered when designing computer (informatics) systems for archaeology concerns precisely the conceptual modelling of the data. The activity in question brings together two important subjects: the abstract nature of the modelling process and the selective nature of the source archaeological data.

Within the structure of the formal model both subjects lead to the conceptualization into categories as a way to organize knowledge (Bommara 2004), which integrates the representation techniques with ontological analysis.

Figure 1. The etruscan sanctuary of Pyrgi.

Pyrgi: Collection and Classification of Archaeological Data

The experiment has been conducted on the documentation and the conceptual digital modelling in of the Etruscan sanctuary of Pyrgi (Figure 1). It had been studied for years in its different aspects, from its urban and territorial characteristics and its connections with the port of Caere to the analyses of the remaining fragments of architectural terracotta (Figure 2). Excavations conducted in 1957 (Pallottino 1971, 1984) brought to light a sacred area upon which there stood two temple complexes, named Temple A and Temple B - endowed with rich architectonic ornamentation - and area C well known as the place where gold foils were found and a rectangular edifice divided into cells was placed against the enclosing wall of the sanctuary (Colonna 1970, 1985). Only a few vestiges of the temple context survived on the site but numerous fragments of deco-

Figure 2. The excavation of Etruscan sanctuary of Pyrgi, from 1957 to 2017.

rations have been found[4] (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. Attention has been given to the study and analysis of archaeological elements that are parts thereof by applying methods and techniques which allow us to grasp the objects on the urban scale and in full detail (Colonna and Pelagatti 1990).

Therefore, presented here are the processes that followed as well as the results of some experiments

4 Three documents carved on gold tablets found around Tempio B on July 8th, 1964 during an excavation campaign go back to the 6th or the beginning of the 5th century B.C. The remains of considerable historical and linguistic interest for Etruscan archaeology 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.

with the objective to bring out important aspects of the concerted efforts of architects and archaeologists working at the site. The present endeavour was taken up with the intention to implement a process never before attempted in relation to the data concerning the Sanctuary of Pyrgi. The aim of the study is to valorise cultural heritage by enquiring into the possibilities and the modalities for documenting and popularizing archaeological heritage (Van Dyke 2006).

The work was divided into the following stages: analysis of all the documentation available; semantic classification of the updated material (bibliographical documents, archive sources, images, archaeologists' drawings); integration of available information with data from surveying/surveys of existing objects[5]; 2D/3D philological reconstruction of the original state of elements which did not survive, taking departure from archaeological data; and preparation of a database for the digital documentation of the models and related heterogeneous information[6].

The initial, propaedeutic stage of these activities involved the acquisition and archiving of all the updated data relative to the two temples (see Figure 3). However, the main body of the existing documentation is made up of archive materials, bibliographical information and notes from excavation sites. So, the path taken has been directed towards systematizing and communicating heterogeneous information that includes documentation of the current state and a reconstruction of things lost (Callieri et al. 2015; Remondino and Campana 2014). The research made it possible to fine-tune a digitalized enquiry methodology aimed at extracting and systemizing unstructured or semi-structured data contained in archaeological documents but always related to the research carried out in situ (excavation diaries, archived documents, historical documentation, data gathered by archaeologists, drawings made during various excavation campaigns, and interpretative hypotheses).

The central point selected was that of the transition from problems involved in representing data that were essentially textual or that contained few graphic models to subsequently defining the ontologies of the domain of archaeology. The construction of archaeological models from textual data passes through the definition of categories and relations between them, allowing the construction of mental models also linked to a reality that no longer exists, such as the sacred area of Pyrgi. Two classes of problems are inherent in this particular operation: the first one is that the modelling of objects that no longer exist is always linked to subjective interpretation; the second - that the definition of the categories and relationships and the construction of models are always linked to the concept of scale[7]. To address such questions, one has to grasp the meaning of all the terms to be able to adequately express and represent -- through models -- the relations between them. Model constructing operations do not follow a hierarchical scheme. They have to embrace, instead, a complex network of relations within which the representations of objects of a structural and functional nature are associated. The analysis of textual documentation has proved to be fundamental for elaborating concepts, that is, for defining in proper terminology the elements to be described and represented and subsequently to be able to distill the relations --

5 Survey of existing elements was conducted by integrated methodologies for non-contact survey: topography and 3D laser scanning for substructures, Structure from motion (SfM) for architectural terracotta.

6 Systematization of data within a platform and their diffusion is part of the Digital Heritage defined in the Charter on the Preservation of the Digital Heritage published by UNESCO in 2003, as: "cultural, educational, scientific and administrative resources, as well as 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."

7 Models of all types, whether ideal or real, provide a determined quantity of information related to the detail level at which it has been realized. The concept of scale (or the ratio of reduction) is directly linked with that of intrinsic uncertainty (also referred to as the error of graphicism) and is characteristic of all graphic models. Knowing this value – conventionally linked to the capability of the human eye to distinguish clearly two adjacent lines (0.2/0.3 mm) – immediately allows one to characterize any graphic elaboration in terms of metric uncertainty, a parameter that from this standpoint depends solely on the adopted ratio of reduction. In this way it becomes possible to evaluate a priori the uncertainty level to be dealt with in the stage of realization, starting with any scale drawing (towards the Project); and vice versa, it must be taken into account as soon as a surveying campaign is organized because the data have to comply from the moment of acquisition with the requirement of equal or lower drawing uncertainty (towards the Survey). For example, a drawing in 1:50 scale allows the intrinsic uncertainty level ranging from 1/1.5 cm (0.2/0.3 mm x 50 = 10/15 mm = 1/1.5 cm): so, in the stage of acquisition it will be necessary to select instruments and methods which meet this prerequisite.

criteri per la catalogazione / elementi archeologici	PERIODO		CLASSIFICAZIONE			MATERIALE ARCHIVIO			EL.FISICO		LOCALIZZAZIONE			ACQUISIZIONE	
	580-480 (A)	480-230 (B)	livello costruttivo	livello funzionale	livello decorativo	modelli grafici	testo	immagini	si	no	Antiquarium Pyrgi	Museo Nazionale Etrusco Villa Giulia	Santuario Pyrgi	rilevamento non a contatto	virtualizzazione dato archeologico
stereobate muri perimetrali	●	○	●	○	○	●	●	○	○	●	○	○	○	○	●
stereobate muri trasversali	●	○	●	○	○	●	●	○	●	○	○	○	●	●	●
stereobate muri interni	●	○	●	○	○	●	●	○	●	○	○	○	●	●	●
stereobate pavimento in tufo	●	○	●	○	○	●	●	○	○	●	○	○	○	○	●
terrazza	●	○	●	○	○	●	●	○	○	●	○	○	○	○	●
podio	●	○	●	○	○	●	●	○	○	●	○	○	○	○	●
copertura	●	○	●	○	○	●	●	○	○	●	○	○	○	○	●
ordine tuscanico fusto	●	○	○	●	○	●	●	●	●	○	●	○	○	●	●
ordine tuscanico base	●	○	○	●	○	●	●	●	●	○	●	○	○	●	●
ordine tuscanico capitello	●	○	○	●	○	●	●	●	●	○	●	○	○	●	●
architrave lastre rivestimento	○	●	○	○	●	●	●	●	●	○	●	○	○	●	●
architrave lastre rivestimento	○	●	○	○	●	●	●	●	●	○	●	○	○	●	●
architrave lastre rivestimento	○	●	○	○	●	●	●	●	●	○	●	○	○	●	●
architrave lastre rivestimento	●	○	○	○	●	●	●	●	●	○	●	○	○	●	●
spiovente sinistro lastre rivestimento	●	○	○	○	●	●	●	●	●	○	●	○	○	●	●
spiovente sinistro lastre rivestimento	●	○	○	○	●	●	●	●	●	○	●	○	○	●	●

Figure 3. Classification of existing archaeological documentation.

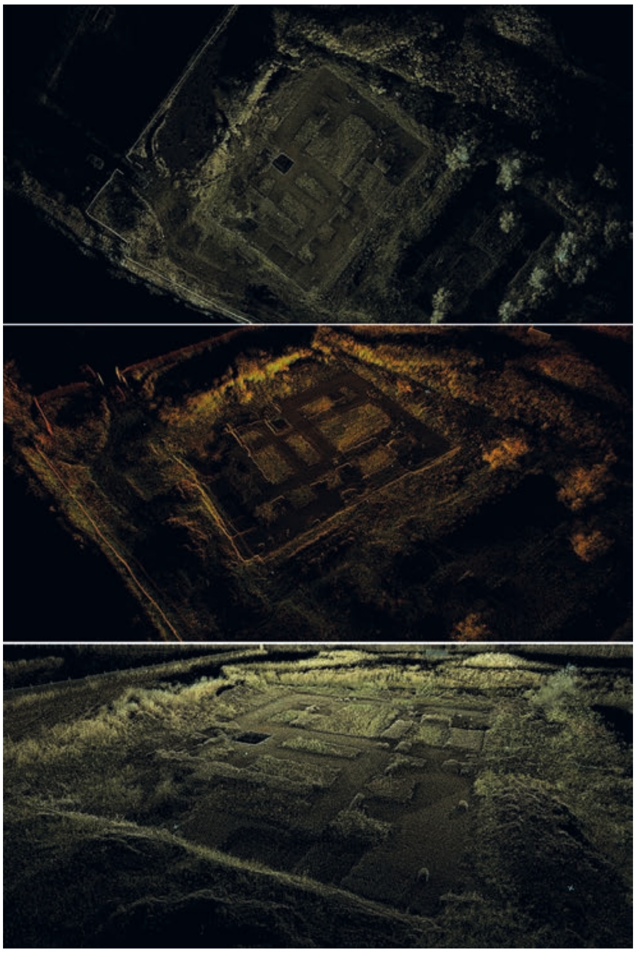

Figure 4. Analysis of available documentation for extraction of categories (surveying of Temple A).

Figure 5. Survey of Mythological high relief (Temple A).

hierarchical or not -- obtained among various classes of elements.

Issues in Model Construction

A complete and organized collection of archived documentation – graphic and textual – as well as the cataloguing of data at our disposal were necessary to maintain unchanged the informative contents while passing from archaeological documentation, mainly textual, to that with a large number of graphic models. The criteria adopted for cataloguing objects (Batley 2005) are strictly connected to the characteristic properties of archaeological objects: registered name, historical period to which the object belongs, a list of documents concerning Temple A and Temple B. Such a classification made it possible to structure out a documentation that having started with semantic classification of the component parts of the object of study links indissolubly their cognition to the study of the sources at our disposal and to archaeological interpretation. The goal is the construction of models that are as objective as possible (Apollonio et al. 2013; Brunetaud et al. 2012). Familiarity with the methods and techniques for data acquisition legitimized an a priori assessment of the results to be obtained through surveying various existing objects (structural remains and fragments of architectural terracotta), which in turn constitute a solid basis for understanding the whole structure but also through the survey of the intangible carried out by studying texts for the purpose of constructing theoretical models. The processes of acquiring and elaborating data have been conducted through integrated surveying: 3D laser scanning for structural elements, SfM – and direct surveying for controlling measurements – to construct models (Cipriani and Fantini 2015) of architectural terracotta (see Figure 4). Data acquisition and processing through SfM concerned two types of elements. On the one hand there were those useful for the ideal reconstruction of Temple A

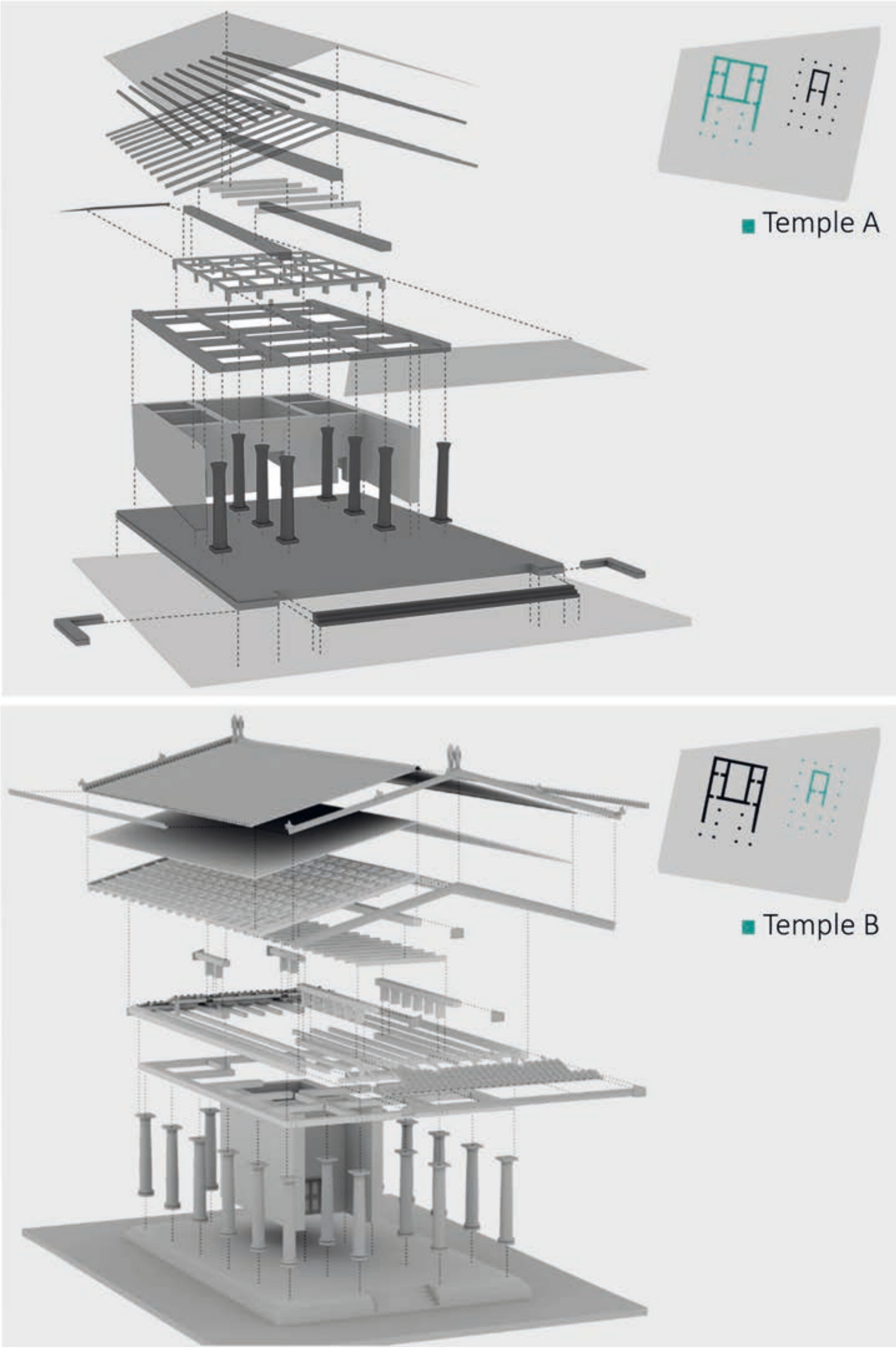

Figure 6. Philological restoration of Etruscan sanctuary of Pyrgi (Temple A and Temple B).

and Temple B, from which profiles have been extrapolated and geometries reconstructed. On the other hand, there were those sculpted, excessively fragmented and unattributable to any architectural typology. Such elements could be catalogued not only through photographic images or survey elaborations executed by applying traditional methodologies, but also with the help of three-dimensional model correctly scaled and placed in the Cartesian conception of space (Figure 5). They are useful for putting forth reconstructive hypotheses on the basis of data that are objective metrically, geometrically, chromatically and materially.

The successive stage, however, concerns the 3D reconstruction of Temple A and Temple B in a virtual environment (Figure 6). At this stage a comparison between researchers who work in different fields of inquiry – 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

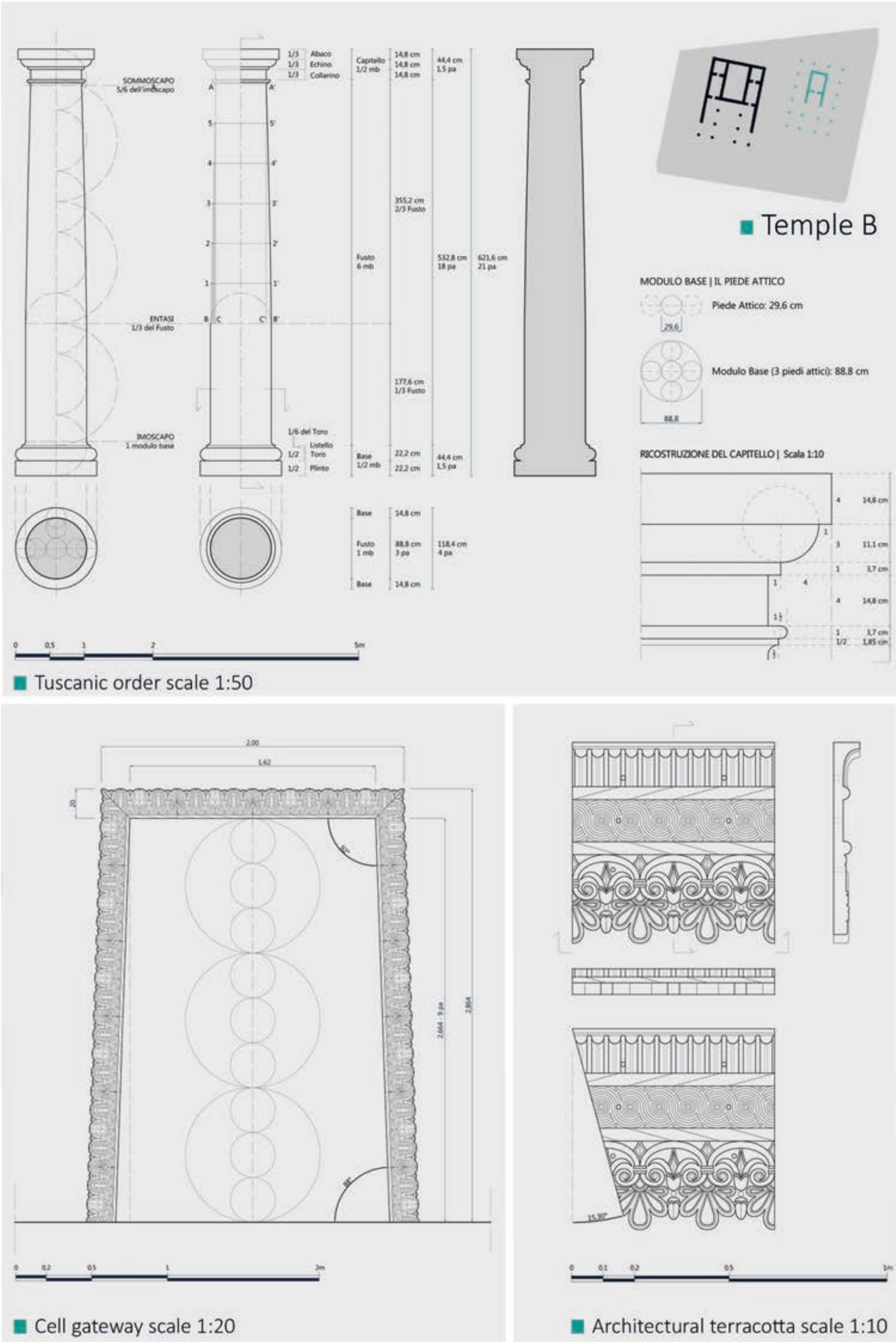

Figure 7. From textual data to 3D ideal model: composition and relation between classes of elements (Temple B).

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 2D representation and for 3D modelling (Figure 7). The virtual model obtained – a synthesis of the knowledge gained from the study and the analysis of data gathered – had already been defined previously in the construction elements and in the decorative ones. Defining generative and directive profiles and curves made it possible to reconstruct the most likely original appearance of Temple A and Temple B at the time of their construction.

Problems addressed in close collaboration with archaeologists are related to the interpretation of the dichotomies between the data provided by various sources to the overall composition of the object, to the process of transition from the complexity of ar-

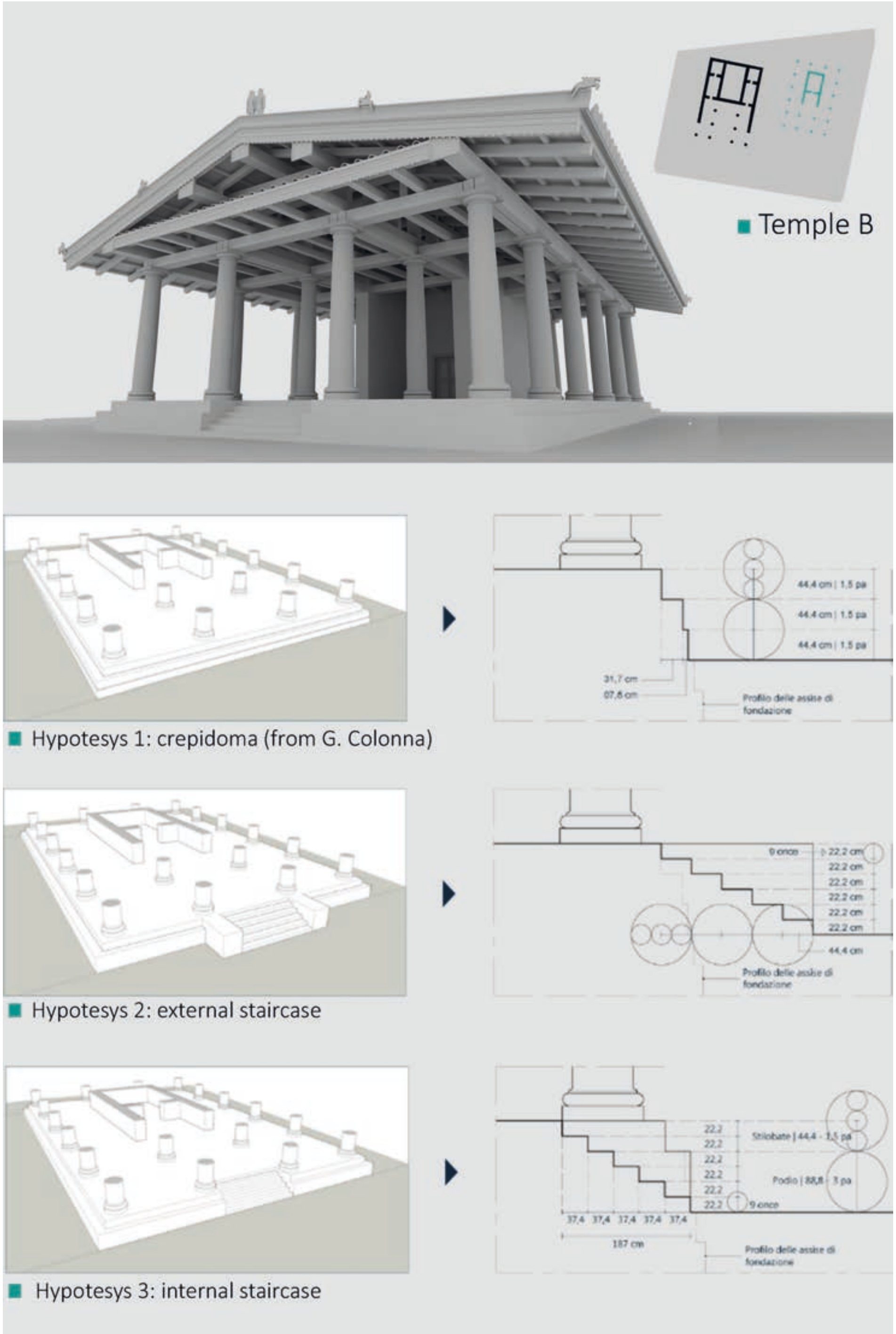

Figure 8. From textual data to 2D ideal models (Temple B).

chitectural object to the complexity of single pieces and decorative elements, as well as to the selection of the level of detail. There are three typologies of scientific validity and credibility used here: certain elements (ruins), certain or highly probable elements (repeatable or speculative), obtainable from preserved structures of embellishments, elements obtainable from graphic reproductions from the past that are subjected to verification for possible errors or misinterpretations, and deduced elements (obtainable from structures and decorations of similar buildings, based on typologies and features characteristic for the historical epoch).

For example, one of the issues addressed concerns the structure of the access to Temple B. The historical and archaeological sources predicted a high crepidoma (hypothesis from Giovanni Colonna) or an outside staircase. The construction of a 3D model, however, led others to hypothesize the presence of an internal staircase based on the unit of measure and

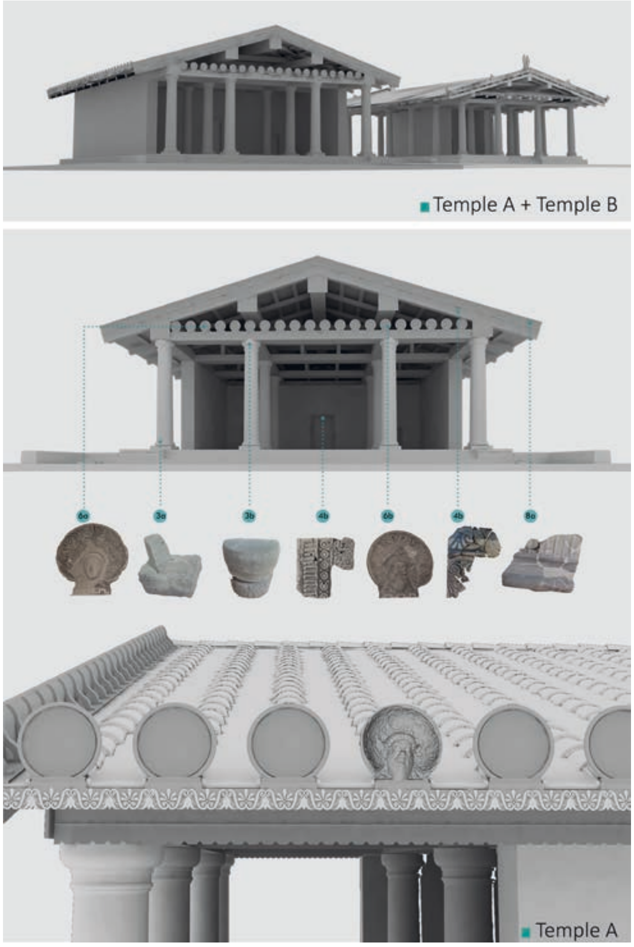

Figure 9. Philological restoration of Etruscan sanctuary of Pyrgi (Temple A and Temple B).

the size of blocks of tufa that were used (Figure 8). Another issue is related to the podium of Temple A. No remnants, descriptions, or any information about it has survived which would make it possible to determine its original structure. In order to construct its complete model, archaeological objects of the same period endowed with analogous characteristic features were taken into account (Tempio di Vulci), and on this basis its structure has been hypothesized (Figure 9).

Digital Solutions for Managing Archaeological Data

All typologies of the models, totally reconstructed and partially derived from surveying, have been used as an instrument of communication between various professionals involved in the research. The sources of data described above constitute modalities for gathering and presenting - in a transparent manner - the whole reconstruction process to be carried out – the objectives, methodology, techniques, arguments, characteristics of research sources, results and conclusions. The database constituted represents the point of departure for the road leading to a complete knowledge. Digitalization makes it continuously and immediately applicable, useful for faster and simpler dissemination of heterogeneous contents: data sheets with information on existing objects, graphic 2D elaborations, 3D models, photographic images, multimedia contents, and virtual itineraries.

A digital archive – a process whose objective is to furnish the possibility of dynamic and interactive reading – constitutes an innovative modality for the unification and diffusion of heterogeneous data dispersed throughout a territory but at the same time homogeneous in relation to criteria adopted for cataloguing and virtualizing existing and non-existing elements (Figure 10). A complete and neatly organized collection of graphic and textual archive documentation was necessary to maintain intact the informative content during the transition from archaeological documentation, mainly textual, to one with a high number of graphic models. This principle (Principle 7.1 of the Siviglia Charter 2004) reconfirms the necessity to prepare an objective and exhaustive documentary basis which examines the whole research process linked to the creation of digital contents for virtual archaeology (Evans and Daly 2006). In the domain of archaeological architecture data acquisition, virtualizing and communicating are processes that ought to converse with one another. Data systematization experiences spring from the necessity to create structured information, to archive it, to put it at the disposal of users, and also from a strong necessity of cataloguing a mass of data.

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, which applications to use. The fundamental subject is the definition of connections between data structured according semantic categories and able to organize different information, like texts, images, 3D/2D/1D models linked by transitive relations that make possible the transition from the general to the particular, from the simple to the complex. Much attention will be given to the choice of interface, that is an informatics means most adequate for commu-

Figure 10. Archaeological documentation of Etruscan sanctuary of Pyrgi from 1957 to 2017.

nicating and using data as broadly as possible[8]. Construction of digital archives in archaeology can have multiple effects on the spread of information, not always distributed on a large scale for reasons of space and costs. Defining an open system based on the integration of specific and heterogeneous competencies involved in the study of archaeological heritage provides the point of departure for structuring out a process whose objective is knowledge.

The launched project serves as a tool to study in-depth the problem related to the classification and communication of archaeological data through heterogeneous models. The approach adopted enabled us to analyse the question of ekphrasis linking it to the use of technologies serving digital representa-

8 Software open source for archiving heterogeneous data of the archaeological heritage (http://3dhop.net).

tion. While in the past textual description was considered superior to representation by virtue of its capacity to express contents inaccessible otherwise, nowadays the situation seems to have been reversed. Thanks to the technological evolution of informatics systems, descriptive operation has been designated to static and dynamic virtual models. Ekphrastic representation – through words – is efficacious because it can give life to a visual story (models). The choice to apply procedures based on object grouping and the articulation of concepts can be said to enrich and specify the classification operations while at the same time offering innovative forms of enjoying archaeological objects which can now be studied, analysed and related to one another. Representations become indispensable for analysing, interpreting and documenting cultural heritage on a large, medium and small scale. The application of all the most innovative technologies ensures the possibility to exchange objective data open to further interpretations. Elaboration of models for static and dynamic representations as well as creating databases for interactive use online constitute a model for managing archaeological heritage that became more accessible, complete, applicable and usable.

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3D Modeling to Reconstruct a Paleontological Site: Museum of Casal de' Pazzi in Rome

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Abstract

Today, 3D modeling allows the creation of sophisticated reconstructions in the field of Paleontology that until a short time ago could only be obtained with traditional techniques and hand-made drawings. An interesting methodological application is the Museum of Casal de' Pazzi in Rome. In this case 3D modeling has allowed the reconstruction, starting from the discovery of some finds, an "Ancient Elephant," a "Urus," and a "Neanderthal Man". Modeling was performed with the help of scientific data and experienced paleontologists and anthropologists. 3D models were completed with the "digital sculpting" technique, allowing a more accurate reconstruction of the shape and appearance of the animals and hominin. The models were subsequently used for multimedia and interactive communication, describing the history of the place where the Museum is located.

Keywords: paleontology, 3D modeling, museums

Introduction

The discovery of the Pleistocene Rebibbia – Casal de' Pazzi complex and its excavation, carried out by the Archaeological Superintendence of Rome from 1981 to 1985, allowed scholars to learn more about the oldest phases of human settlement in Rome and, more generally, in the Italian peninsula (Anzidei and Gioia 1990). The excavation work covered over 1200 square meters. It led to the discovery of a vast Pleistocene deposit, consisting of a portion of the bed of an ancient river. The site is located on the right bank of the Aniene River, at an altitude of 32 m above sea level. Layers of gravel and pyroclastic sand (rock of volcanic origin) characterize the site where scattered lithic elements and fossil bones were recovered.

The bones mainly belonged to large mammals such as the ancient elephant (Palaeoloxodon antiquus), the Urus (Bos primigenius), Hippopotamus amphibius, Cervus elaphus, Dicerorhinus sp., and aquatic birds. In the lowest level, almost on the bottom of the river basin, they also found a fragment of parietal bone from a human skull. Overall, about 2,200 bones and over 1,700 lithic tools were recovered. Due to the river nature of the deposit, they show a secondary deposition with different degrees of rounding.

In terms of the number and size of finds, the animal species that symbolizes the site is the ancient elephant (Palaeoloxodon antiquus), represented by remains of tusks (25 whole tusks and 50 fragments), molars (60 intact molars, 120 fragments), fragments of the pelvis and skull and the long bones (Gioia 2004).

After arranging the site protection and security measures as early as 2000, a museum path was erected to properly communicate the complex issues resulting from the site. Verbal and visual communication was selected to get the most out of the new technologies (ICT). Visual and/or interactive communication aimed at involving visitors as much as possible to keep their attention.

State of the Art

ICT reconstruction and the interactive and multimedia communication of archaeological areas draws upon some experiences that have been characterizing the city of Rome in recent years. ICT does have a great "democratic" potential due to both its ability to handle a large amount of information and offer new access modes. The digital processing of information allows users to enjoy "worlds" created from paths and ways that they select. Those who curate a museum staging may either establish a guided path or leave the user free to navigate, move, and dive into familiar stories with the desired level of depth. Visitors decide the level of interaction with the scenario, possible mode of navigation, automatic tours, and specific point-of-view details. This freedom to browse a museum is very different from what was available just a few decades ago. Unless they followed a guide, visitors were left alone. They were supposed to have a specific background in order to enjoy and understand the artistic and cultural heritage on exhibition. Today, the amount and quality of information and "views" that the new museum offers can be best enjoyed by any type of user, whatever their level of knowledge. The multimedia reality, with its new communication quality on the one hand, and the ability to accommodate a greater amount of information on the other, turns the museum into a truly novel, indisputably, democratic system.

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 our 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 Domus 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, enabled the reconstruction of the mosaics, decorated walls, polychrome floors, basalts and other artefacts present in the patrician Domus of the Imperial age, located beneath Palazzo Valentini.

Celebrations for the bi-millenary of Augustus' death (19th August, 14 AD) helped enhance 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 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 organization of 'Journeys into Ancient Rome' (Viaggio nei Fori 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 unprecedented effort, razing an entire neighbourhood to the ground and digging it down to the 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. It showed the emotional experience of life during Roman times, when officials, commoners, soldiers, matrons, consuls and senators walked beneath the arches of the Forum. Among the remaining colonnades there were the tabernae, namely offices and shops and, among these, a nummularius, a kind of currency exchange office. There was also a large public lavatory, with some remains 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, today's equivalent 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.

Research Objectives and Development

Our research aims at identifying one or more representation/reconstruction methods, in lieu of the traditional drawings of animals that lived in the Pleisto-

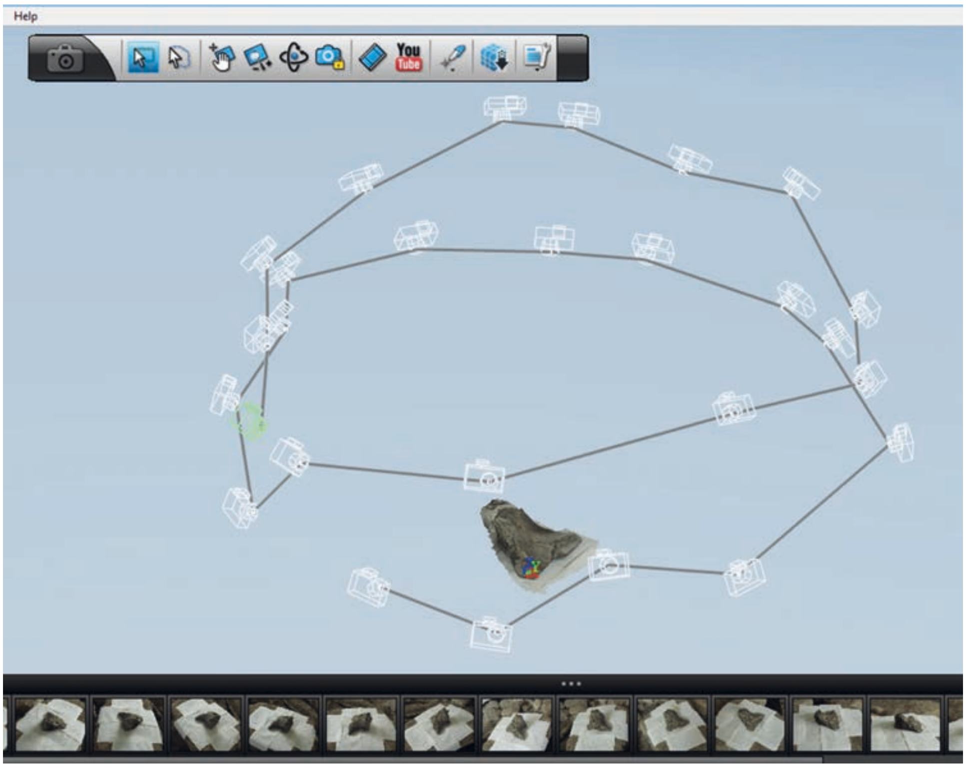

Figure 1. Stereometric frames obtained with 123D Catch (Image processed by M. Camicioli).

cene Deposits (Manzi, Salvadei, & Passarello 1990). In particular, our attention focused on the Pleistocene Museum of Casal de' Pazzi in Rome, where remains from 200,000 years ago had been found. The first part of this research focuses on the 3D reconstruction of the animals, the second one on the use of 3D models for multimedia communication outputs describing the history of the site (e.g., Lock 2003). Given the presence of some artifacts and fossils, 3D modeling allows us to reconstruct the animals that lived in the bed of the river (Empler 2006). In particular, the reconstruction process focuses on an "Ancient Elephant", a "Urus" and "Neanderthal Man". Modeling is based on scientific data and, when those data were absent, the models benefited from the expertise of paleontologists and anthropologists, who had followed the whole 3D procedure.

The research consists of the following phases:

- Identification of "references";
- Survey of objects present in the deposit;
- Realization of models based on low resolution "low-poly";
- "High-poly" modeling through "digital sculpting";
- Retopology and reprojection of details;
- Texturing;
- UV mapping;
- Rendering.

Identification of References

The first part of the reconstruction process is based on the identification of "references." These should be reliable in terms of the size and shape of the animals under study. In most cases, the "references" of an object to be modeled are assumptions previously hypothesized by other scholars who have had the opportunity to define and redefine based on new discoveries the most plausible appearance of any animal being studied. To make 3D models of the most important finds in the areas of Casal de' Pazzi, such as the ancient elephant, the urus, and the Neanderthal, reliable reconstructions had to be put together. They needed to show the following views:

- image of the animal, front view;
- image of the animal, perspective view;
- image of the animal, 3/4 view.

The type of "references" can be of a varying nature, such as a graphic reconstruction or a photograph. Most importantly, they need to be as reliable and consistent as possible with respect to the number of views listed above. Where there is an inconsistency

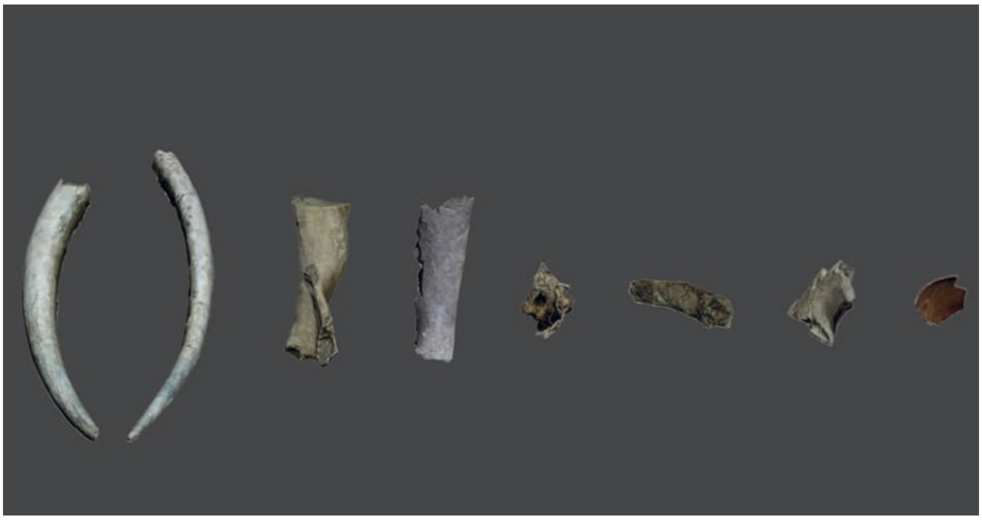

Figure 2. Low-poly models of the finds (Image processed by M. Camicioli).

or reconstruction gaps, the opinion of paleontologists or anthropologists becomes crucial.

Survey of Objects Present in the Deposit

In regards to the 3D survey of the finds existing in the site, a photomodelling (Sammarco 2012) procedure was used. It consists of taking photos following some specific techniques:

- Take photos in a circular pattern;
- Take pictures at a minimum of 2 different levels in height;
- Take pictures at the same angle from one another (30/45°);
- Have an adequate ambient lighting (not too much light, not too much shade);
- Take several photos (at least 50) and some additional pictures for poorly visible de tails.

Before the shots, it is advisable to surround the finds with white cloths or paper sheets, to distinguish them from the surrounding environment. At the end of the "shooting", photomodelling can be obtained with appropriate applications like Autodesk "123D CATCH" (Meneses 2013), among others. The photomodelling software generally returns files in .obj format, which can be used by most 3D modeling applications (Figure 1).

Realization of Models Based on Low Resolution "Low Poly"

The first phase of 3D modeling provides for the generation of models based on low resolution "low-poly" (an abbreviation for "low polygon", i.e., a 3D model consisting of few polygons).

The procedure involves the following steps using 3D Studio Max (Segatto 2016):

1. alignment of front and perspective "references" in their respective views (front and side, right or left), so as to form a right angle between them;

2. insertion of the 3D model of a parallelepiped (Box), positioned between the two images and scaled in such a way as to have its sides aligned with the contours of the figures, both in the front and perspective view;

3. duplication of "edges", i.e. of the sides, of the "Box" and alignment along the contours of the figure, alternating the front view and the perspective (the greater the number of duplications of the sides, the more precise the border alignment). The "symmetry" command allows choosing an axis to reflect the modeling operation and minimize 3D modeling (Figure 2);

4. division of internal "edges", i.e. the sides of the polygon faces, to increase the "density" of the mesh and make it "softer".

This phase yields a low-poly model with the following characteristics: Low-poly Ancient Elephant: 37,800 polygons; Low-poly Urus: 1,208 polygons; Low-poly Neanderthal: 1,348 polygons.

Figure 3. Levels of subdivision: Level 1: 20,000 polygons ca.; Level 3: 350,000 polygons ca.; Level 5: approx. 6,000,000 polygons (in the image) (Image processed by M. Camicioli).

"High-poly" Modeling Through "Digital Sculpting"

At the end of the low-poly modelling step, with models made up of a small number of polygons, high-poly modeling increases the number of polygons of the mesh. This phase takes longer, given the higher complexity of the mesh resulting from the additional quantity and quality of details needed to make the model more "realistic". It is necessary to import low-poly models into a different software for "artistic" modeling, such as Zbrush (Keller 2011). Zbrush has a number of "tools" that allow one to "sculpt" very fine and complex details on the surface of the model (this is why it is called "digital sculpting"). To generate a video output, some parts of the models should be modeled separately rather than sculpted inside the mesh; for example, the eyes and clothing of the Neanderthal must be modeled as separate "tools", albeit being part of the mesh. In this way, they can be animated independently.

First Step of "Sculpting": Subdivision of the Mesh | To sculpt very complex details on the mesh, such as wrinkles, creases or the micro-details of the skin of the elephant, it is necessary to increase the number of low-poly polygons through the "split" command. Upon each subdivision, the number of polygons quadruples. Polygons become increasingly smaller and more compact, increasing the density of the mesh.

Second "Sculpting" Step: Modeling and Progressive Sculpture | As a rule, the mesh should not be split too many times all together; subdivisions should be performed from time to time, depending on the type of detail to sculpt: at the lowest levels of subdivision, the 'larger' details can be modeled. For example, the anatomical features (limbs, fingers, tails, and so on) whereas at higher levels, smaller and finer details are applied. This avoids a "pixel-looking" mesh, which should rather appear clean and uniform. As to sculpting and modeling, ZBrush offers the "brushes" tool that provides a great variety of features and options (Figure 3).

Third "Sculpting" Step: Micro-Sculpture Through "Alpha" Brushes | After modeling the general structure of a character, micro-details are subject to the final sculpting, such as the sculpture of the porosity of the skin, wrinkles, creases, and hair. Zbrush offers special brushes called Alpha. Unlike normal brushes, Alpha brushes sculpt directly on the mesh through the transparency channel. In this case, to create the full pattern of the creases of the elephant skin, or the fur of the Urus, the brush uses an image of a portion of real elephant folds; the brush is then passed over

Figure 4. Fibermesh: Neanderthal hair and beard (Image processed by M. Camicioli).

the whole surface to sculpt according to the same fold pattern and a different orientation and scale. This process ends with the creation of a complete pattern.

Fourth "Sculpting" Step: Fibermesh, Creation of the Hair | To confer more realism to animal models (excluding fossils), the Fibermesh command generates the fur of animals and humans (Figure 4). This tool sets the shape, color, type and appearance of the hair to be applied to a selected area of the mesh (the human skull, for example, or the tip of the tail of the two animals). Fibermesh consists of polygons. This makes the file heavier, sometimes compromising the hardware computing performance. We recommend to properly assess the Fibermesh settings, seeking a balance between the fur realistic appearance and the lightness tool. After completing the high-poly phase of the models, through separate tools and Fibermesh, retopology helps prepare the models for the subsequent animation phase.

Retopology and Reprojection of Details

With the described method, the high-poly model goes back to the low-poly step, albeit with different structural characteristics. These are essential to enable an effective animation of the 3D model. At any rate, the high-poly quality is not lost with Retopology, thanks to its subsequent phase of details reprojection. The retopology model allows the rearrangement and decrease in the number of polygons of the mesh. When using a 3D model for animation, the high-poly model is discarded. In fact, the quality and density of polygons do not allow a smooth walk-through. The low-poly, retopologized model is low-poly like the initial one, but it exhibits different characteristics. The rearrangement and decreased density (quantity) of polygons allows an efficient animation of the critical points of the model, especially the joints.

Retopology must always be carried out from a copy of the high-poly model and can operate in two ways: 1) manual method: polygons are arranged manually one by one (the "symmetry" function halves the work); 2) "fixated" automatic method: polygons are rearranged and decreased through the ZRemesher automatic control; later, some critical points are manually adjusted through the ZModeler command. During the animation phase, the movable parts of the model structure (arms, legs, tail, and proboscis) need a specific topology of polygons for an efficient animation: this is possible thanks to the creation of the edge-loops.

The edge-loops, in a "retopologized" model, are the portions of mesh that connect the mobile section to the whole body. Hence, they indicate the real anatomical joints (junction of arms, legs, tail). An edge-loop must have a higher density of polygons at the attachment of each joint and have a uniform arrangement of polygons (square or rectangles only). The edge-loops allow a smooth and realistic animation of joints. Once the model retopology has been completed, the quality of details of the original high-poly model must be reprojected on to it. To do this 1) the retopology is selected and only the high-poly model is visible, bringing it to the lowest level of subdivision. 2) In retopology you must use the Projects command to reproject on its surface the details of the first layer of the high-poly model. 3) The high-poly model moves to the second level of subdivision while retopology is split; then, the Projects command is activated again. You repeat the last step until retopology has the same number of subdivision levels of the high-poly model (in the case of characters, you can get up to 6 levels). Reprojection returns a single model. At the lowest level, you have a re-topologized model; at the highest level, you have the high-poly model, exhibiting the same quality as the first high-poly model previously generated. At this time the original high-poly model is no longer used.

Texturing

Having the retopology and high-poly in a single model by simply changing the level of subdivision (from 1 to 6 and vice versa) represents another key step for the final realization of the model - the exportation of maps. The texturing step characterizes the mesh through a Polypaint procedure for characters, and Spot Light for bone finds. Polypaint is the command used to color the mesh. It makes use of a standard brush, with the sculpting functions disabled and RGB color enabled. The RGB standard panel spreads the prevailing color consistently across the surface, such as the gray color of the elephant skin. On the other hand, to draw the small details of the skin, tusks and other areas, the Alpha Channel, renamed Alpha RGB is used. As with sculpting, these allow one to repeatedly draw the same module on several parts of the mesh (for example, a portion of skin folds or pores) to finally put together a single pattern.

In this case, the Symmetry function is disabled. Asymmetry of micro-details is not necessary to confer true realism to the model. The Spot Light is the most common way to apply the texture. This technique allows the texturing of fossils. Photos taken to create them in 123D CATCH (Meneses 2013) also allow originating Bitmap Textures, for an extremely accurate coloring, as in the original finds.

The steps involved are as follows:

1. import model and pictures for a clear display of the 6 main views (plant, side prospectuses and bottom);

2. overlay of one of the photos on the view corresponding to that of the model;

3. via the Spot Light function, the model is colored with the picture as a layer above;

4. reduce the photo size to see the result;

5. repeat the above steps for any other available views.

UV mapping

After creating the texture, with a single model including a retopologized low-poly model for animation as well as a high-poly, you can get the same high quality of detail of the high-poly model (subdivision level 6) on the low-poly retopologized model (subdivision level 1) through the UV mapping. The generation of UV coordinates, known as UV mapping, is a process to apply a texture or any type of two-dimensional image on a 3D model. Coordinates and the relevant X and Y values are generated on a Cartesian plane (automatically, manually or a combination of both). These are then assigned to each polygon of the mesh; in this way, each polygon has the required coordinates for the assignment of a certain portion of the 2D image. By putting together all polygons in a two-dimensional Cartesian space, one gets the overall space in which the image is applied, or from which the maps of the various characteristics of the mesh are exported.

This process is similar to an unwinding of the 3D mesh on a two-dimensional plane, with contours corresponding to the cuts applied to the model for 2D unwinding. The Polypaint Texture or Spot Light can be created irrespective of the UV maps; in other words, they can be created on the model even before UV mapping, but cannot be exported as image files to be reapplied to the model. This can be done (for other types of maps, too) only after generating the UV coordinates. The UV positioning in a model including both low-poly and high-poly (on two different levels of subdivision) is a prerequisite to transfer the quality of detail of the high-poly to the low-poly model, since the UV coordinates are the same. This transfer of the detail quality occurs during the so-called "baking."

In this phase, the model achieves its highest high-poly quality to export the various types of maps, each referring to a specific characteristic of the mesh: Texture Map (color map); Normal Map (map of normals); Displacement Map (map of polygonal deformation); Cavity Map (map of "excavated" details); Ambient Occlusion Map (shadow application map). After exporting these maps from the high-poly model and applying them to the low-poly (thanks to their shared UV), the latter acquires the properties and quality of detail of the high-poly model, while the number of polygons remains unchanged. Therefore, the resulting model has a high-poly quality and the low density of polygons of a low-poly. This is the type of model required to proceed with animation.

Rendering

During the animation phase, the maps are applied after the various sequences, to maintain the file light, without compromising the fluidity of the animation process (Empler 2006). However, to get an idea from the outset of how the model will appear during rendering, maps are applied for an initial preview, and once applied, can be edited (Brito 2010). Each map includes a series of editable parameters (e.g., a higher or lower intensity, or a different brightness or color range). By implementing various combinations of the map parameters, and the various maps, the model can take on a completely new look, since it is influenced by the interplay of several factors.

Finally, the choice of material to apply to the mesh (Siddi 2010) is equally important for the final quality of the model; a suitable choice allows an ideal simulation of "real" parameters, like the bounces of light on the surface, or the quality of shadows between the various parts of the model. Once the low-poly, retopologized model is complete with the high-poly maps to apply on top, the model is ready for preparation for the animation. However, if you also need to realize explicative rendering images of definitive models, you can also use a simple high-poly model. The low-poly and its textured maps do not exceed the high quality of detail of a high-poly model. The rendering output results from the retopologized model. It is brought to the highest level of subdivision of the high-poly, i.e. the maximum quality. After "baking" maps and exporting the low-poly, retopologized model as an .obj file, preparation for the model animation begins. This step precedes the animation proper and includes a number of steps to make the model fully mobile.

Instead of Zbrush (Keller 2011) modeling software, Maya offers a better performance during animation. Since the video is not complete yet, we will analyze only the phases immediately preceding the animation, to get a preview of the result.

First Step: Creation of Joints | Once you have imported the low-poly model into the Maya animation software, the skeleton, consisting of joints, is created. The skeleton, composed of various joints and individual bones, should not necessarily be too faithful to the true skeleton of the real animal; however, while limiting the number of joints, they should be placed properly, for example in the junctions, to faithfully reflect the junction points of the true skeleton. Several graphic reconstructions of the skeleton of the two animals and the Neanderthal have been collected for this purpose.

Second Step: Orientation of the Joints | Once the skeleton is ready, it is necessary to orient every single joint, to obtain an accurate rotation. Specifically, the axis (X, Y and Z) of each joint must be aligned with those of the other joints, especially those that are part of the same chain. A chain, in this context, is a series of joints arranged along the same direction until they are interrupted by another chain that is connected but oriented in a different direction. In other words, there exists a chain for the arms, one for the legs, one for the bust, and so forth.

Third Step: Skinning | After preparing the skeleton and orienting each joint, the so called "skinning" begins. A given portion of the mesh is assigned to a matching joint. This connection between joint and portion of the mesh is performed by painting that portion of the mesh. The edges are colored in blue (zero influence) while the central body is red (maximum influence). They are then shaded with hues of green and yellow. To begin skinning, you need to push the Smooth Bind command. It performs a first automatic skinning that can be manually changed according to your needs.

Fourth Step: Rigging | The last step to prepare the model for the animation is the composition of the rigging. The creation of manual commands (called "handles") connected to the joints, through the previous skinning, allow the various parts of the model to move. The rigging phase is essential to allow the widest range of movements of the various parts of the model. From here onwards, the model is moved, or better, posed for the different frames, until animation ends (see Figs. 5-7).

The completion of the rigging of characters starts the animation proper. First of all, it is necessary to preset certain elements such as the creation of the background, the screen resolution, and the lighting. The preview, in the form of Animatics, shows its structure and the surrounding scenery.

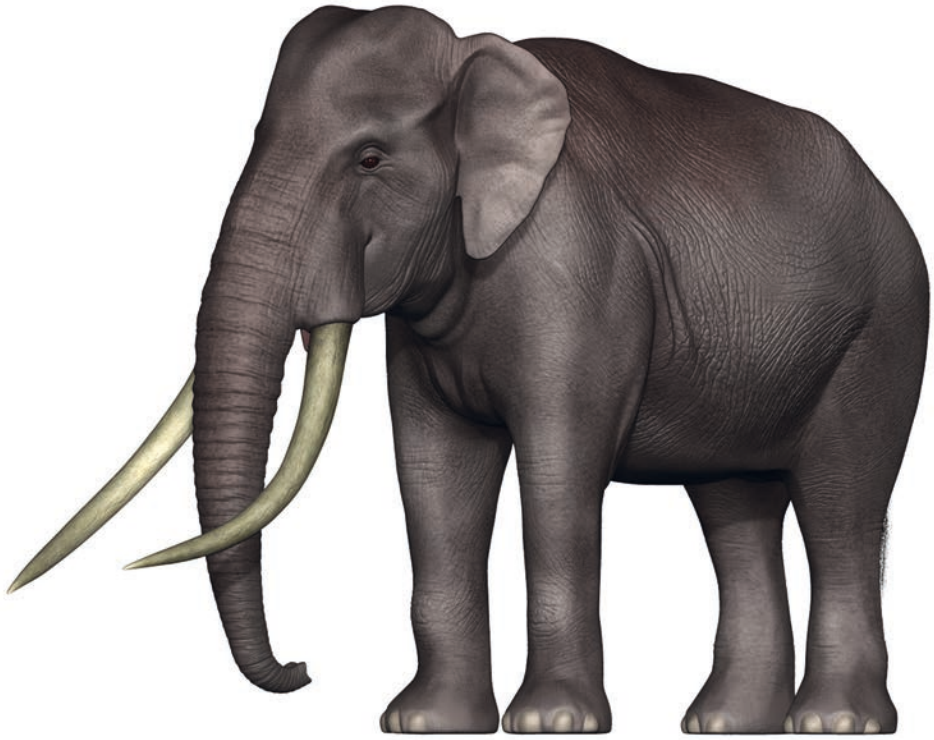

Figure 5. Rendering of the ancient elephant (Image processed by M. Camicioli).

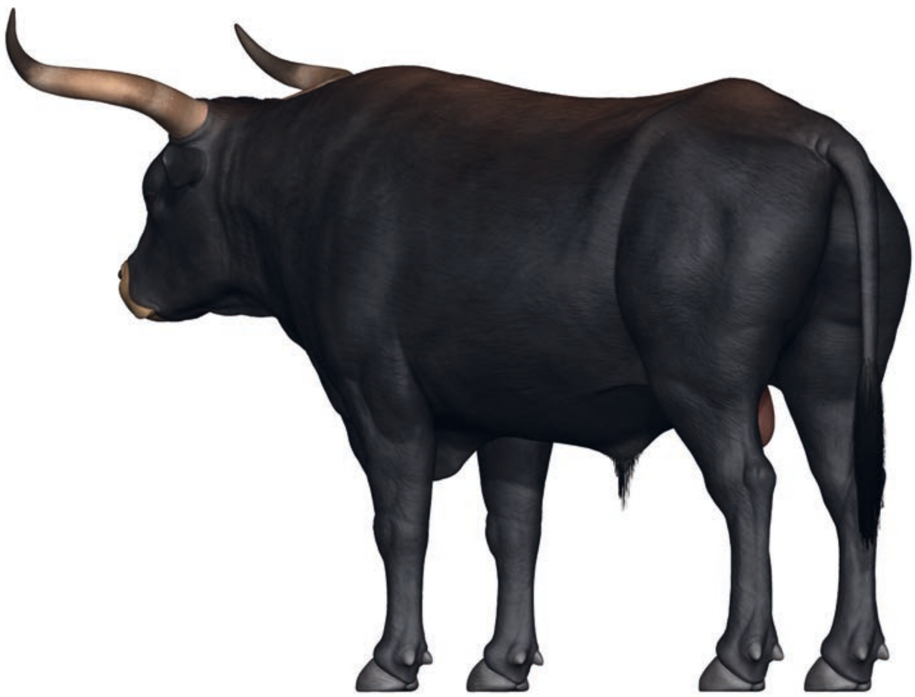

Figure 6. Urus rendering (Image processed by M. Camicioli).

Conclusions

As we have seen, the potential of 3D modeling in the field of Paleontology is considerable. It is possible to reconstruct the appearance of an animal starting with the fossils recovered in a prehistoric deposit and integrating data with elements on the muscles and skin taken from the literature or from references

Figure 7. Rendering of Neanderthal (Image processed by M. Camicioli).

found at other sites. When this is not sufficient, paleontologists and anthropologists give their advice. 3D models, as previously illustrated, can generate videos in which the life of animals in the environments in which they lived has been reconstructed. A further important aspect relates to 3D printing. In this case, research can follow two directions. On the one hand, the production of 3D prints of reconstructed animals (with muscles and skin) produces physical objects. In turn, they can undergo a manual transformation in the event experts believe that some parts need to be modified in the light of new findings or new research outcomes. The second option is the reconstruction of the missing parts of bone finds. Bone and muscle reconstruction assumptions can be tested differently from traditional techniques.

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Mixed Reality, 3D Printing, and Storytelling: Methodologies for the Creation of Multi-Sensory Scenarios in the Field of Cultural Heritage

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Abstract

In the last years there has been a revolution in the use of cultural heritage from a communicative and interactive point of view: the user looks for exciting experiences and a new "contact" with the site. So, we have to propose innovative means of communication and learning to meet these changing needs. The field of archeology and historical reconstruction of buildings, provides new ideas for research in this field: the three-dimensional reconstruction of historical and cultural buildings involves the ludic sector, and it is also effective for the diffusion of the historical sites. The paper aims to promote a methodology that begins from the reconstruction of documentary sources and archaeological excavation, it shapes a three dimensional model and prints a real prototype. Printed object can be perceived better and offers both a visual and a tactile approach. The possibility of integrating the physical object with augmented reality systems, appears to be today the innovative field of research of this methodology. Also, this system makes possible an immersive perception of the site. Dissemination moves from the bidimensional area into the three-dimensional reality of space that surrounds the "user".

Keywords: 3D printing, mixed reality, communication, dissemination, cultural heritage

Introduction

Today, it still happens too often to see confused and bewildered visitors in a museum hall or an archaeological park. If you ask them to describe their experience, many reply they have seen, metaphorically speaking, a "cemetery of stones". It is therefore still difficult to communicate what sites represent. Teaching materials, when present, are most often unclear and seemingly designed for specialists. Other groups of visitors are just allowed to watch in uncritical contemplation (De Felice and Volpe 2014). In order to overcome this gap, technological aspects are often emphasized, while the true issue is methodological and cultural. Today, it seems indeed almost impossible not to use the new technologies in the field of archeology as well as in the survey step, post production of data step, study of reconstructive hypotheses starting from survey data. Daly and Evans defined "Digital archaeology" as follows: "Digital Archaeology explores the basic relationships that archaeologists have with Information and Communication Technology (ICT) and digital technology to assess the impact that such innovations have had on the very basic ways that archaeology is performed and considered" (Daly and Evans 2006)

At present, the aim and evolution of archaeology is not to keep popularizing the digital technologies; it is necessary to develop a procedural path to realize effective virtual platforms for users to enjoy an immersive and learning experience. If the aim is to disseminate scientific knowledge, scientific data should be the starting point. Historical research, on-site survey, the acquisition of point clouds through laser scanner and photogrammetry, the subsequent critical elaboration of data, represent the foundation to accurately interpreting and reconstructing an object in the digital space from historical, metric and geometrical viewpoints.

Scientific research is now gearing toward the virtual migration of reality and the creation of 3D shapes that can be experienced as real spaces (Bercigli, Parrinello, & Picchio 2016). Graphical solutions should transmit historical and scientific knowledge while creating different forms of communication giving rise to multiple feelings and reactions among users. However, access to virtual and augmented reality is generally based on devices like viewers or tablets and smartphones. This is why many believe that a multimedia, interactive museum should be based only on sophisticated interfaces and on the man-machine interaction.

The use of virtual reality through viewers or mobile devices entails several issues. Different by their nature, they are due to the human perception system. First, users tend to concentrate solely on what is defined by experiential marketing as the "wow factor". This results from the use of the technology itself, and the information content is left in the background. Second, facilitated access to virtual reality, regardless of where the user is located, may decrease the level of empathy with the archaeological site and the artifact, with the perception of the historical context or with the material-based texture of finds. Finally, the issues related to the image and the "short circuit" that is created are quite evident. This stems from the contrast between the visual signals and the perception of movement, creating the so-called "motion sickness" (Chardonnet, Mirzaei, & Merienne 2015)

However, if the communication interface was a physical model, the user would have a direct emotional, unfiltered relationship. The physical quality of an object can be easily perceived. This happens because senses are predisposed to seize the relevant signals, with no sensory "short circuit." The ease of understanding a stimulus implies a higher rate of response on the part of the user (Empler 2015). Obviously, this uses traditional media that does not provide any added value to the new communication techniques. Therefore, the integration between physical models and digital interfaces could give rise to a global exploratory system based on audio-visual and tactile sensations. This process creates a rapprochement between the physical and virtual space and amplifies the values of each.

Recent Solutions: Some Examples of Integration Between 3D Printing and Multi-Sensory Experiencess

Here, I analyze some international experiences that are based on the integration between the physical object and digital communication technologies:

1. University of Camerino and the "Santuario della santa casa di Loreto";

2. Hitachi Digital Imaging Systems Project and the "Uffizi Gallery in Tokyo";

3. "Glass Beacon Museum" in the Trajan's Market.

In the first case, the researchers set up a space consisting of a multimedia table, with a scale physical model of the Basilica of Loreto obtained through 3D printing. This model can be "queried"; it works like an interface in order to access contents concerning the Shrine. To enable the interactive mode, "proximity sensors" were placed in certain areas of the 3D printed model. The interaction is managed by the Arduino technology: this is a hardware platform that, through its software, allows for the connection of proximity sensors to an electronic screen. The informative content is automatically activated once the user taps or touches a region of interest. Moreover, the touch screen allows the user to access more information. Finally, 3D viewers and game engine technologies create an immersive experience: the user is catapulted into the virtual and three-dimensional reconstruction of the Shrine as it existed in the seventeenth century. It makes use of a VR viewer and a binocular projection system. Visitors enjoy the virtual space through a motion simulation system. (Feriozzi, Meschini, & Rossi 2016). The model acts as mediator between the real world and virtual reality, and it becomes a three-dimensional interactive platform to access historical, metric and geometrical information. It is therefore an object of interaction and a means of access, while virtual reality comes about separately and later. From a perceptual point of view, this is a stand-alone interaction system, based on visual sensations. Still, users have a limited possibility to move; they are bound to a screen and to the virtual reality system, which necessarily implies for visitors to hold a fixed position.

The second example, “The Uffizi Gallery in Tokyo”, fits into the category of the 2D digitization of cultural heritage. The Exhibition features real size copies of some of the most famous paintings from Uffizi Gallery. The interactive screens, placed next to each painting, not only allowed the user to access the information content but, thanks to them, the work could be appreciated in its smallest details. The data base offered images acquired at very high resolution (1200 pixels per inch) or gigapixel with accurate colors and without any geometrical distortions. By zooming on the painting area of interest, the user could see details virtually indistinguishable to the naked eye, in addition to capturing details concerning the pouncing or the engravings in the initial drawing. This can be described as augmented reality. This type of digitization represents a valuable aid also to scholars. They can carefully examine every detail or the techniques of “construction” of the painting itself. From a perceptual point of view, it enables an interaction stimulating visual and tactile sensations, in so far as it was possible to touch the works themselves and feel the texture of a brush stroke or an incision. Paradoxically, although they are not original works, this exhibition allows users to appreciate the artistic perfection of such art. In addition, these tools provide complete and accurate information on multiple levels of communication and interaction and involve as many users as possible. While the direct experience of an object or artifact remains important, the example described above allows developing new forms of entertainment and communication and a procedure that can be replicated in places and situations where gaining access to a cultural asset proves to be difficult.

In the experimental project of the Glass Beacon Museum at the Trajan’s Market in Rome, the Google glasses, augmented reality viewers, were put at the disposal of visitors. During the exhibition, visitors followed a pre-established path across the exhibit. The path was established by the distribution of beacons, namely low frequency bluetooth repeaters. These detected the user’s position and automatically activated the informative content displayed on the viewer. In this way, visitors could access text, images and video directly from their display. In particular, some sculptural elements underwent a virtual reconstruction and were enriched with the reconstruction of decorations and chromatic spectra. Such reconstruction (loaded into the database to which viewers were connected) was overlapped to the real object thanks to the Google glasses; therefore, the user could appreciate the virtual decorations, now lost, on a physical and real element. In this way, the displayed object is not a means to access the information content but becomes itself the subject of interaction. You would define this as mixed reality; visitors enjoy the real space in a shared manner by overlapping virtual elements either in a stand-alone mode or on-demand. The user has a richer experience thanks to audiovisual content; however, they do not have a tactile experience because these are original fragments and works that cannot be touched.

The mixed reality (MR), contrary to VR and AR, seems to be the ideal solution to integrate the physical object and advanced communication technologies. MR allows overcoming and increasing the information received through perceptive data only. Contrary to virtual reality, it does not cause motion sickness and does not alter the context perception. You can offer to visitor a tactile and material experience, audio-visual content, as well as innovative communication and learning tools. The difficulties related to augmented reality have to do with the perfect overlap between the real and virtual image, in addition to the user traceability. The superimposition of a virtual content on a physical element has been based, until now, on systems that can be defined as “passive.” ARTag, or geometrical markers in augmented reality, monitor the user and the camera in the viewer, tracking its position and direction, and once you know the real position of the camera and viewers, optical collimation and 3D digital models are projected into the real marker. In this way, the point of view and the center of projection, are constrained and preferential. The systems of interaction between the user and virtual elements, are also based on technologies borrowed from game engines like Kinect and Leap Motion 3D (Empler and Fabrizi 2016), which in turn may be defined as “passive,” since they track, from the outside, movements on the basis of the user’s position.

In order to overcome such a restricted point of view, a viewer called HoloLens exploits the principle of the hologram: the image projection system is internal and does not need any external marker. The recognition of the surrounding environment takes place by means of an internal digital camera. This system can be defined as "active." In this case the camera tracks the environment and not the reverse. A hologram is "drawn" internally, in real time, on tracked objects whose position is known to the viewer. An infrared sensor, still inside the viewer, deriving from Kinect technology, detects movements and guides the virtual man-object interaction. However, the user cannot freely move in the three-dimensional space because the processor must reprocess and re-map the environment in order to project a new image.

A recent technology called Project Tango developed by Google (currently only available for smartphone and soon for viewers too), however, has revolutionized the Mixed Reality system. It was designed as a mobile device, tracking the morphology of the space around the observer thanks to a depth sensor. The three-dimensional space is mapped and recorded in an integrated points cloud with RGB values in real time. The device, therefore, returns a three-dimensional digital model, contained in the internal memory, where it inserts the virtual objects where the user is located. The user can move into the surrounding space where virtual objects are inserted; at the same time, they can interact with projected items whose perspective varies with the user's position. This can happen because the digital objects are inserted into the three-dimensional model of the real environment and the overall projected image.

Proposed Solution to Offer Multi-Sensory Experiences: Between Virtual Reality and Reality Reproduction

If the goal is to make the public understand an archaeological artifact and its history while creating multi-sensory learning scenarios, it is necessary to go through a process of analysis, synthesis, recording, reconstruction, and communication following a workflow consisting of these steps:

1. Data acquisition via integrated techniques of laser scanner, photogrammetry, direct survey GPS, and topography;

Figure 1. 3D printing and virtual model are overlaid by using mixed reality.

2. Reprocessing and interpretation of data and construction of a NURBS (Non Uniform Rational Basis-Splines. It is a mathematical model for generating and representing curves and surfaces) or polygonal model;

3. Archeological reconstruction and interpretative hypotheses on the basis of geometrical properties and historical analyses;

4. Retopology and transition from a hi-poly to a low-poly mesh model to lighten the software upload required to generate real time applications;

5. Texturing of the resulting three-dimensional model;

6. Design and print a real prototype with a 3D printer in the most appropriate scale;

7. Processing of virtual platforms for communication.

Thanks to the many technologies available on the market, partly presented above, it is possible to integrate the tactile properties of the printed prototype with the visual ones to create multi-sensory museums.

For example, when framing a scale model through mobile devices or viewers, you may virtually visualize the three-dimensional model characterized by accurately reconstructed decorations (Figure 1) (Aliperta and Gira 2015). The overlap between the virtual and physical representation is possible because the virtual model and the prototype are obtained from the same initial data, based on the accuracy of

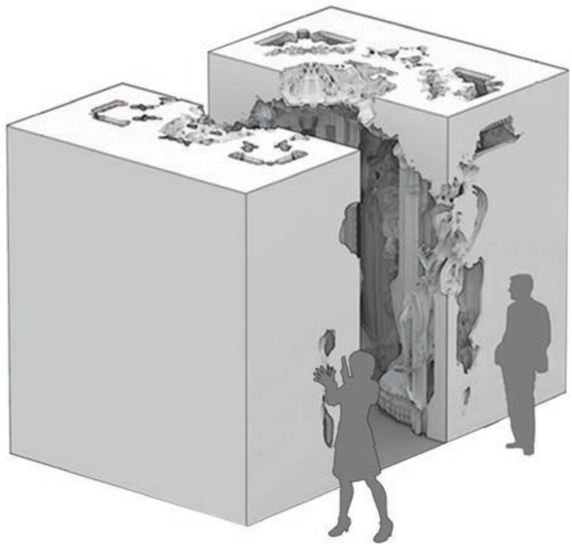

Figure 2a.

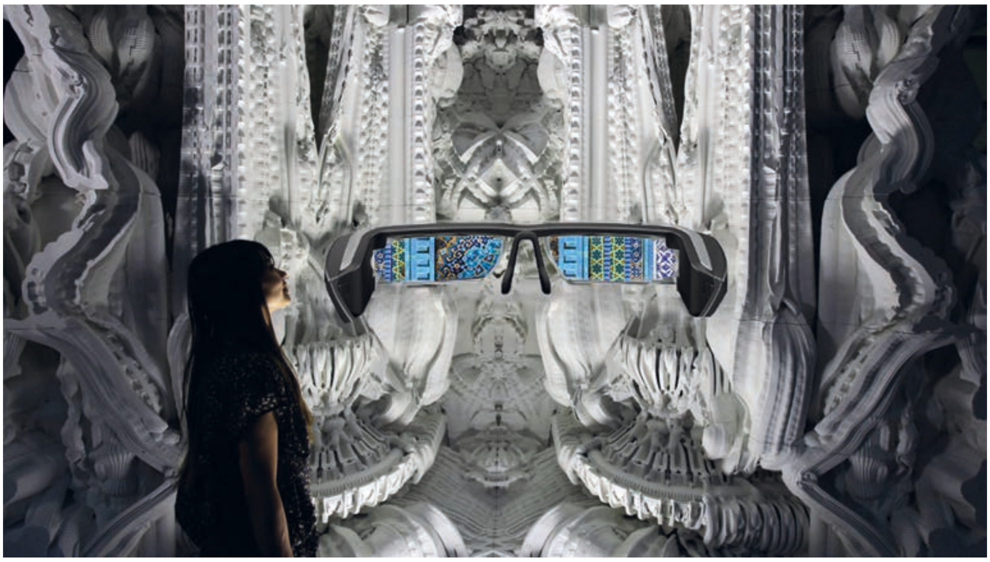

Figure 2. An object printed on a larger scale increases the immersive effect (2a), 3D printing and mixed reality help stimulate visual and tactile sensations (2b).

the survey and the exact geometric reconstruction. The three-dimensional digital image is stored in a cloud database, which loads data on viewers or devices when it recognizes the geometric marker previously recorded on the prototype. The prototype should be printed in the most appropriate scale in terms of both overall dimensions and details. When the staging space is larger, the perceptual impact can be increased by printing the object or part of it at a larger scale. In this way, thanks to the use of viewers like Google Tango and mixed reality, instead of a summary image, a more detailed, immersive image is returned; the user can interact with the object and interpret it seamlessly (Figures 2a-2b). It is possible to recreate real environments in which the visitor can enjoy the entire space available. Viewers allow tracking and creating a three-dimensional model of the environment in which it moves and project images, objects and elements onto it. The mode of interaction is not a virtual space; it is real and dynamic (Bercigli et al. 2016)

However, the multi-sensory scenario is not complete yet. "Storytelling" plays a fundamental role in conveying information, stimulates curiosity and generates a better learning environment. User surveys show that narration and interaction are their main expectations: by customizing their own experience, they want to enter into the stories and interact with the characters (Pescarin et al. 2012).

An archaeological object is made of tangible and intangible properties. Archaeology deals not only with the collection, analysis, and interpretation of

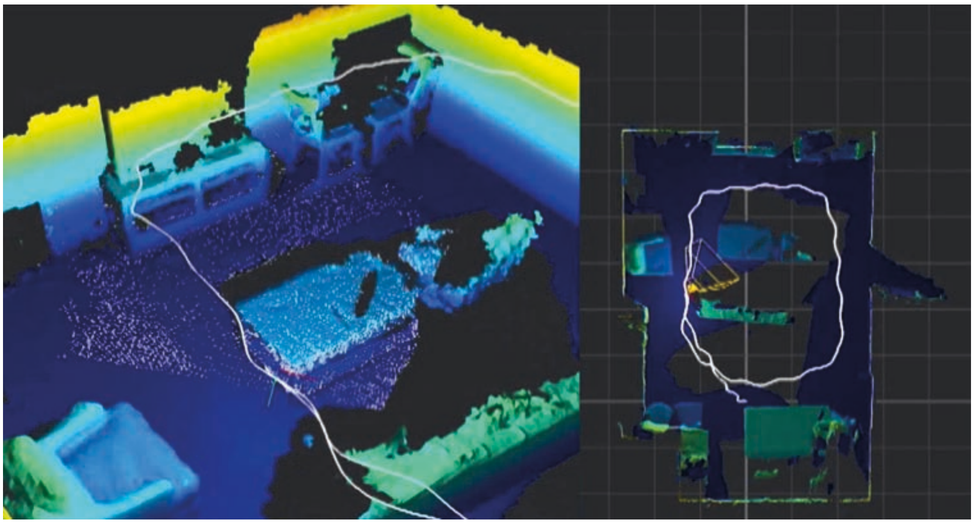

Figure 3. Google Tango tracks space in real-time and creates a point cloud. The numerical model is stored on the device memory, and it will update as the real environment changes.

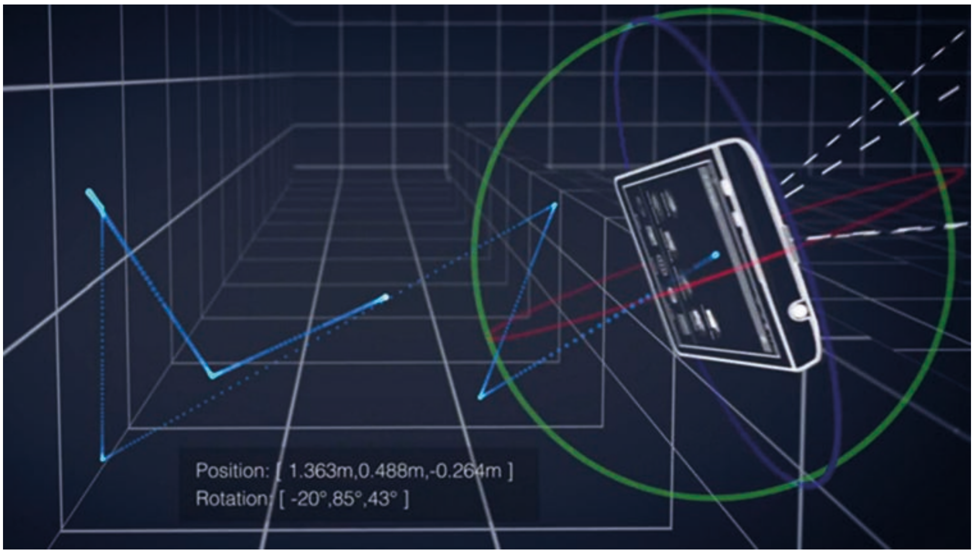

Figure 4. Point cloud has its own coordinate system x, y, and z. Virtual objects are placed in the point cloud's coordinate system and the viewer's position is drawn in the same coordinate system. Users and objects interact in virtual space.

data; it tries to reconstruct stories, cultures, events (De Felice and Volpe 2014). In one of his famous books, Umberto Eco said: "…the past must be recognizable, but there is a need for real characters, like ordinary people….they make us understand everyday life and their behavior tells us a lot more about their time than history" (Eco 2012 as cited in Ferdani et al. 2016). It is therefore desirable and possible to "populate" the static images loaded on the cloud of reconstructions with virtual characters, i.e. archetypes adapted to the specific context, thanks to mixed reality.

The real printed prototype becomes the scenery of a virtual "show": images and stories involving visitors are projected onto it. The physical object expresses itself and the archaeological artifact it represents, through the characters and their culture. This is how the overall nature and complexity of an archaeological find are communicated, and how participation and sharing of a museum space are stimulated.

Once again, mixed reality can help us thanks to the use of Google Tango technology, which creates a three-dimensional and digital model of the space surrounding the visitor and the printed prototype is part of it (Figure 3). This digital model, inserted into the device memory, has its own system of three-dimensional coordinates, where the position of the observer is plotted (Figure 4). In such digital space, both the virtual representation of the archaeological artifact and characters, in the form of avatars, are projected. User, physical model, reconstructions, and virtual objects belong to the same reference system. Visitors can therefore interact with them thanks to the device-embedded leap motion systems (Figure 5). The interaction system makes these figures selectable and queryable: they can communicate the scientific and the historical content in relation to the character played. Different narrative paths can be developed for the different types of site users (Figure 6).

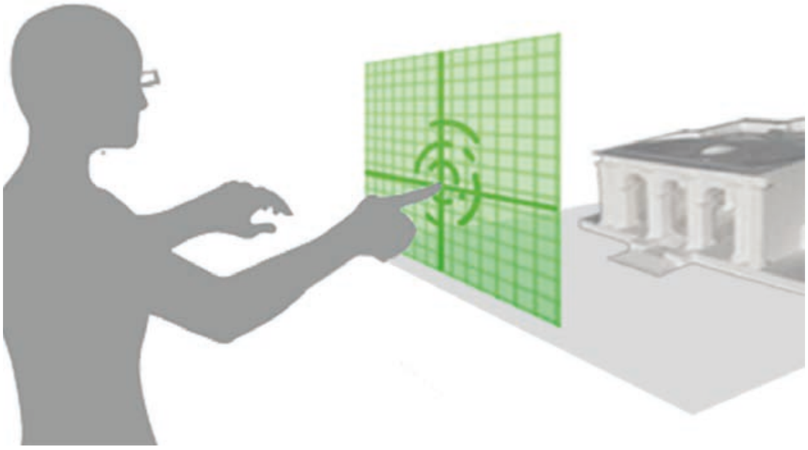

Figure 5. Users, real objects, and digitized objects interact virtually in the space thanks to a specific system, like leap motion, integrated into the device.

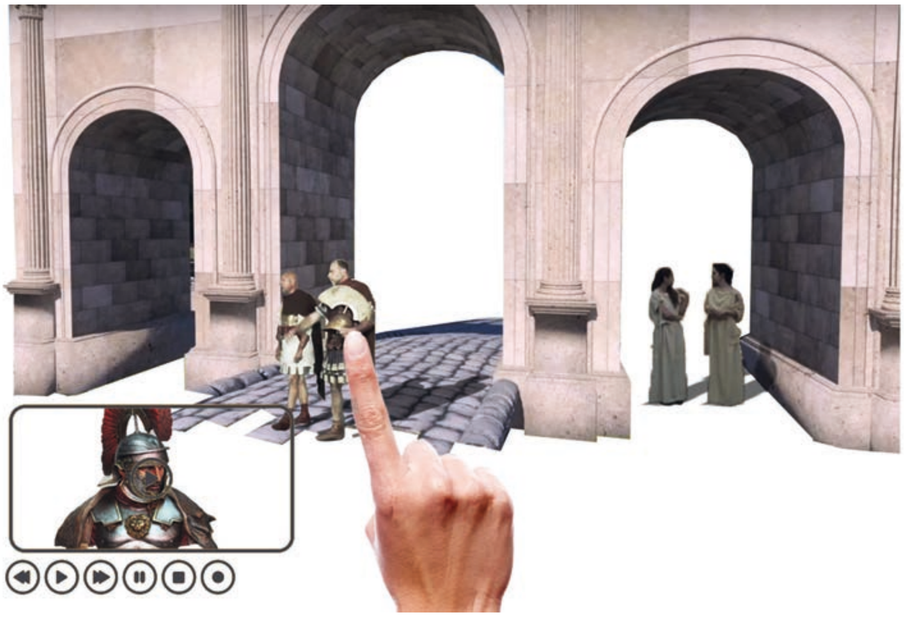

Figure 6. Characters and avatars are delectable and queryable. You can assume different narratives, in relation to the different site's users.

Space becomes dynamic. It includes real objects, reconstructions, stories, and relations; the perception of digital space varies thanks to the physical model generating a new spatial awareness, a reality where users can find their own narrative and empathize with the context.

Conclusions

Analysis, documentation and interpretation connecting to digital technologies, computer graphics and 3D printing, contribute to the dissemination of scientific knowledge while involving the user. Playful, interactive, immersive aspects contribute to experimental, new forms of communication. The physical model is an "analog" interaction system. It exploits the user's internalized perceptions by leveraging previously learned codes of conduct to approach a different environmental situation (Empler 2015). In the proposed system here, the prototype becomes the container and its contents, and acts as a liaison to access a system of "digital" interaction based on mixed reality. New standards of information and experience are established for the mental, virtual, and real spaces. "Multi-sensory" museums have the potential to become containers of multicultural and interconnected information going beyond the divide between researchers and the public, thus creating an increasingly participative construction of knowledge.

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Tradition and Innovation: From Worksite Plans to Digital Models

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Abstract

The study and analysis of archaeological elements often ranges from very large sites to small objects. This difference in size and type is also present during survey and representation. This idea sparked the proposed study of worksite plans that constitute the only firm link between historical architecture and its representation. The objective is to develop a new interpretation of worksite plans merging massive acquisition technologies with digital representation. The topic is associated with studies on the origins of architectural drawing based on the interdisciplinary union between architecture and archaeology. The objective is to critically interpret worksite plans in order to establish and classify a study methodology. Based on these premises, we examined the key relationship between the metric/formal construction of a 2D drawing (plan) with a 3D model (ideal model). The study is part of the now consolidated drawing/survey/design process which is based on objective/real drawings and leads to a 3D/ideal model.

Keywords: tracings, 2D/3D models, integrated survey

Introduction

The method of incising in stone the working drawing of structural and decorative elements at the real scale (Αναγραφευζ, Anagrapheus, see Inglese 2012) goes back to ancient times. Many archaeologists were immediately attracted to this subject because the study of worksite plans uncovered the process of combining and juxtaposing architectonic elements and provided precious information on stages of work on site. Quite soon the interest in the formal genesis of worksite plans as well as their correspondence to construction elements made necessary in-depth studies of a more distinctively architectonic character: the history of the construction on site was taken into account and researchers understood how the executive design was drafted when there was no light and versatile material like paper at the builders' disposal (Inglese 2016, Inglese 2000).

Already in ancient Greece and then in ancient Rome the necessity to control the project by means of incisions linked architects to the building site. Later, in the Middle Ages, this practice was widely followed at the construction sites of great Romanesque and Gothic cathedrals. Preserved in the cathedrals of Reims (Branner 1957, 1958, 1963; Deneux 1925), Clermont-Ferrand, Noirlac as well as in other cities in France, Spain (Ruiz de la Rosa 1987, 1997), Italy and England, are evidences – incised in stone – of an attempt at working out a common methodology of controlling architectonic elements (Brunet 1928; Bucher 1973,1979; Ferguson 1979). Inside the cathedral of York, for example, one of the most eloquent examples of a tracing house has been preserved: a room of 4x7 m where the whole paved floor is covered by incisions at real scale. Although they still have not been interpreted univocally, it is still possible to recognize the profiles of two rounded arches, a tracing of a

Figure 1. The church of Santa Maria Assunta Cathedral at Terni.

great ogive, a whole series of stained window decorations and of some polylobate fenestration (Harvey 1968; Wright 1985).

In Italy, on site working plans prepared between the Middle Ages and the XVII century are especially widespread in Umbria (Docci and Gurgone 1977; Chiovelli 2011) and in Puglia (Ambrosi 1988). The church of San Salvatore at Campi (Norcia, Umbria) is of great importance in this context. The church was raised to the ground by the earthquake of August 2016, but had already been damaged by the earthquake of 1859, which struck Norcia and its environs. Inside the church, incised on the paved floor of the right nave, there is a complicated drawing in which it is possible to recognize a bell tower complete with its pinnacle, a small lantern and a weathercock with a flag on top. The drawing was executed at the scale 1: 1 and provides in orthogonal projection, the plan and elevation of the original bell tower (Gurgone 1983). In fact, it is a two-dimensional model created for the purpose of cutting blocks of stone to be used in constructing the edifice. The incisions represent decorative elements of the highest part of the church's tower, which some remains preserved in the space under the iconostasis seem to confirm. A "lace" of embellishment of the gabled roof at the pinnacle has been found. It most probably survived when the church tumbled down in 1859. The stone "lace" exactly coincides with the drawings of the very same element to be found in the incisions.

The worksite plans were realized with the commonly used instruments such as the triangle and the compass while construction and decorative elements were represented through planimetric schemes and – at times – through perspective drawings and sections. The application of orthogonal projections of architectonic artefacts provides precious information for the knowledge of the historical epoch in the aspect of architectonic representation. This piece of information proves that the use of essentially bidimensional models had been decisive since antiquity. The practice of preparing worksite drawings was not aimed only at resolving static and construction problems. They ensure stereotomic aid to stone cutters. From this point of view, it becomes clear how important was the study of the geometrical construction of the worksite drawings to be able to understand to what extent they influenced the realization of architectonic elements. To grasp the range of application of these drawings and the part they played in the process of constructing a building, we decided to articulate the problem by identifying two principal types of signs: the first group is composed of assembly drawings or drawings in situ whose role is to help control the po-

Figure 2. Tracings detected on the counter-façade.

sitioning of architectonic elements; the second group has been termed as design drawings for architecture and is composed of the drawings whose role is to design in advance and control elements to be assembled.

Worksite Tracing at Santa Maria Assunta at Terni

The present research concerns the survey of worksite drawings, a practice which has not yet been formed into a definite and well-defined process. In this particular context, the methodology chosen integrates the competences of architects and archaeologists in order to attain as complete knowledge of the object of study as possible. The integrated competences are further supported by techniques applied: the most innovative instruments of 3D capturing (laser scanning and Structure-from-Motion [SfM]/Image-Matching [IM]) have been coupled with direct surveying methods (traditional pouncing[1]). Massive acquisition has been applied for surveying real architectonic elements as well as the worksite drawings. The latter have been surveyed additionally by traditional pouncing in order to achieve results at the scale 1:1. This choice was dictated by the need to experimentally apply the well-established methodology of surveying three dimensional artefacts at architectonic scale. Whereas in this particular setting the use of the laser scanner has become almost a common practice, the subject of worksite drawings raises problems non-investigated so far. In a context where the whole process of cognition – from acquisition to communication – is carried out totally through digital systems, there appeared the necessity to entrust the first registration of data to traditional surveying processes. This stage immediately triggered off a critical and interpretative reading establishing a link between profound knowledge and the analysed elements.

The stage of data capturing is introductory in relation to the realization of 2D and 3D models. Their stylistic analysis and decomposition into constituent geometric elements is – at least at present – an innovative procedure of the research devoted to worksite drawings. The choice of the type of model, of the set of objective data to be selected as well as of the representation code are not, therefore, independent of the quantity and the quality of the data to be com-

1 Pouncing is an art technique used for transferring an image from one surface to another. It is similar to tracing, and is useful for creating copies of a sketch outline to produce finished works

municated.[2] Considering the enormous value of the drawings as testimony, we have raised the problem of utilizing these drawings for reconstructing – both physically and virtually – represented elements. Moreover, the system of incised executive drawings offers us an opportunity to study, analyse, and reconstruct the constitutive elements of an architectonic organism. They can serve as the point of reference when the edifices collapse, are destroyed or there is no information about them because of no maintenance. This is all the more important in the historical period when earthquakes that shook central Italy caused enormous, often irreparable damage. This is precisely the basis for our research which initiated with the worksite drawings on the counter-façade of the Santa Maria Assunta Cathedral at Terni (Figure 1).

Most probably the church was founded in the IX century. Its Romanesque façade was constructed with materials stripped from Roman edifices preserved in the area. Renovation of the church started in the second half of the XVI century, thanks to the artist Sebastiano Flori, and was completed only in the middle of the following century. The new order imposed, with its modern façade and the front portico was completely ready in 1963. The construction of the belfry in the thirties of the XVIII century concluded definitively the great cycle of renovation of buildings in the area (Angelelli 2006; Sturm 2012).

Five worksite drawings were identified on the Romanesque counter-façade with a homogeneous extension on the whole lower strip up to 2 meters (Figure 2). The stone support has composite texture both chromatically and typologically. The represented elements seem to confirm to the hypothesis that they were executed at the time when the façade was being renovated: the correspondence between the incised element and the architectonic one realized on the XVII century portico is easily retraceable.

Among the tracings, we can detect a plan of a binate column and of a half column leaning against a pillar, a section of an entablature and of the column base, an elevation of a column (the shaft and part of the capital, excluding the base). The incisions might have been realized with some blade tools, a hypothesis compatible with the typology and depth of the tracings: the grooves of the incisions rarely exceed a millimetre, which makes difficult their reading and interpretation with the naked eye.

Surveying: Integrated Data Acquisition and Methods

The worksite tracings have been studied with a double objective in mind: to confirm the correspondence between the design drawings and the corresponding built elements and to develop a classification of various typologies of rediscovered signs, a procedure that has not been attempted so far. This result depends on the data acquisition, which has to be reliable and correct typologically. To achieve this particular aim, the study of the worksite drawings has been carried out by applying the processes of integrated surveying. This methodology is already well-established and seems to be more suited to construct an articulated and verifiable system of knowledge. Problems involved in every process of acquisition are compensated by integrating them. Even though instrumental capturing operations prove to be completely mechanical, the operator's experience is fundamental in organizing the stage of the surveying project designed as a function of the final product. The first experimental approach was a massive acquisition of worksite drawings with a laser scanner[3] (Figure 3).

Although acquisitions of details were duly carried out, the massive survey proved to be unsuitable in this case because the grooves of worksite drawings incised in stone are not deep enough to be adequately captured. In order to optimize the results of scans we decided to trace the signs incised in stone with char-

2 The survey operations (in the stage of data acquisition) provide objective information that describe the elements analysed in quantitative terms (coordinates, position, geometry). Instead, the next stage of the survey (data elaboration) describes the quality of the object analysed with reference to the properties contingent of permanent and to any formal aspect concretely determined within a given reality (Bianchini 1995; Bianchini et al. 2016).

3 Leica Geosystem, Leica ScanStation C10, sample spacing 2x2 mm, 3x3 mm and 10x10 mm.

Figure 3. Surveying of the architectural complex. The structured point cloud of the church obtained by laser scanner surveying.

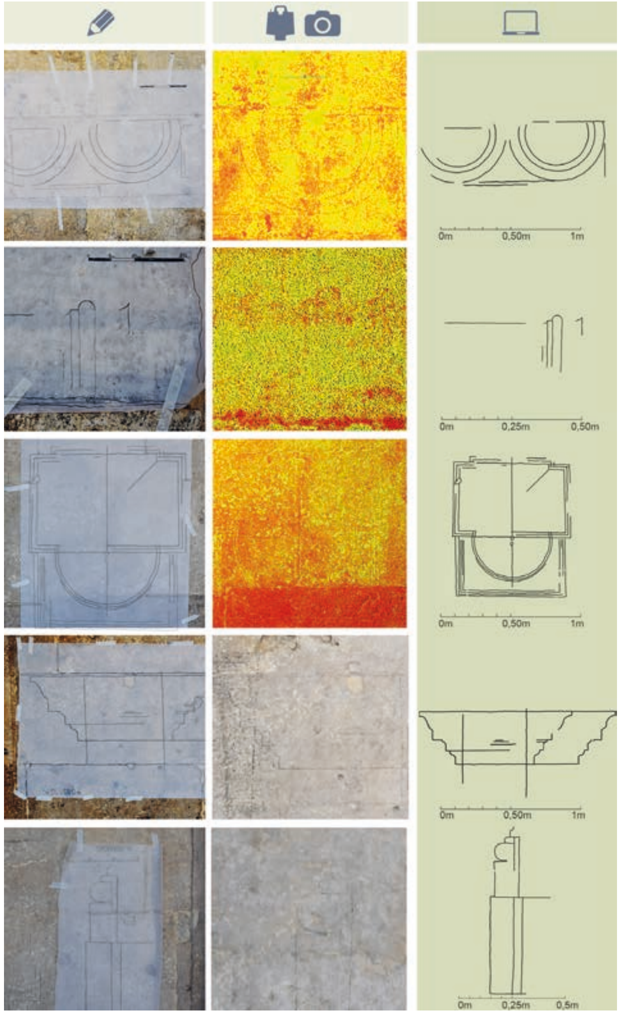

Figure 4. The integrated surveying process of tracings.

coal. This manoeuvre changed the reflectance values[4] of the parts to be surveyed and made the drawings clearly visible. Apart of detail scans of individual drawings, laser scanner survey of the whole portico and the façade of the church were carried out. It proved necessary for a systematic documentation as well as for the acquisition of architectonic elements realized in the façade and found comparable to those represented in the worksite drawings. Massive data capturing with a laser scanner was supplemented by a photographic campaign with the view to realising models of the counter-façade by photogrammetric methods, of architectonic elements of major interest and of a part of the front colonnade. This particular surveying technique proves especially interesting when combined with a numeric model[5] obtained with a laser scanner. Integrating the two methods makes it possible to obtain a metrically controllable orthophotograph of the counter-façade culled from the data from laser scansions and the textured surface from high-resolution photographs. Specifically, although RGB data were acquired with a laser scanner, it was found preferable to entrust the mapping if

4 A fraction of the power that a small superficial area struck by an electromagnetic wave is able to reflect (re-emit). In the case of laser scanning this value can play a predictive role in relations to the physical characteristics a given material (typology, state of preservation) of which the surface of incidence is made or composed.

5 Synthetization of survey datum in which is registered every single information acquired be it metric or chromatic. The term refers to a model whose shape is described by points characterized by their spatial coordinates x, y, z, also known as point cloud.

the surface to the image-based model because of the superiority of the photographic sensor.

For surveying the worksite drawings, the proper techniques for architectonic survey were supplemented by its traditional variety, i.e. pouncing. Tracing incised signs on transparent foil completed information capturing. It was indispensable to acquire data at 1:1 scale in order to make all the signs on the surface legible: because of the irregular nature of stones at the base, it was necessary to add a preliminary stage of recognizing the signs. Pouncing makes possible a direct interpretation of representations at real scale by recognizing the features of architectonic objects hardly visible to the naked eye and made evident through the contrast of graphite and paper.

Surveying operations carried out were planned with the objective of defining a methodology applicable to analogous cases. One again, integration of more techniques and methods yields the most extensive possible knowledge of the sign under analysis and makes it possible to take advantage of the potentialities inherent in each individual methodology (Figure 4).

The Survey: Data Elaboration and Models

Virtualization of survey data enabled the construction of 2D/3D models to compare the ideal datum with the real one in order to verify whether the worksite tracings for constructing the physical element were used adequately (Figure 5). Such an operation is possible by rigorously applying rules of geometry that constitute the only control instrument in this case. Nowadays, digital models become more and more heterogeneous and dynamic both in their creation and management. This proves they could be virtual substitutes of real objects. They come to be expressed through various forms of representation which – by optimizing the univocal transmission of information (metric, geometric, concerning colour, concerning reflectance, etc.) – are applied to simulate more varied operations and make it possible to carry out increasingly more profound analyses.

Construction of models derived from survey data was carried out along two lines: 3D models based on 2D data, for the incised drawings, and 2D models derived from the elaboration of 3D models, for corresponding architectonic elements of the porch. In the former case, the datum at the point of departure is a representation in orthogonal projections. At the initial stage, the 2D data were reproduced in a digital environment. The operation was carried out by interpolating information gleaned from various surveying processes. As concerns worksite drawings, the data provided by visualizing numeric models in reflectance were found to be insufficiently detailed; the signs were hardly visible while their level of detail was not adequate in comparison with the data obtained through pouncing. This acquisition methodology, as has been explained above, is at real scale of representation. The view in reflectance, on the other hand, adds no information of any kind. Precisely for this reason, pouncing results were adopted as the datum of departure for the analysis of ideal models: they were elaborated with the aim of obtaining vector designs. This furnished the basis for elaborating 3D and 2D ideal models (Figure 6).[6]

Design drawings by their nature refer to an ideal model, so their three-dimensional representation cannot be executed through mathematical models: each architectonic element designed follows the rules of descriptive geometry and therefore is well represented by mathematical equations. Such a practice ensures material form and substance to a drawing: one virtually goes once again through the process which connects the stage of designing to that of production of the architectonic artefact on site. In the other case, the data taken as the point of departure were provided by a three-dimensional numeric model of the architectonic elements selected. In this setting, the process of elaboration proceeded from the extraction of two dimensional profiles from a three-dimensional model in which the metrically objective datum proved to be clearly legible.

Elaboration from Structure-from-Motion and Image-Matching completed the cognitive panorama of the area of study: the orthophotograph of the counter-façade was applied to verify whether the photographic acquisition of pouncing had been correct. Photograms for SfM/IM were acquired with a lens focal length of 18 mm (sensor APS-C, equivalent focal length of 27 mm) at the average distance of

6 Model where the shape is described continuously through the parametric equation of the surface from which it is composed. NURBS surfaces are currently one of the most widely used mathematical figures used for this purpose.

Figure 5. Construction of real 3D/2D models of the half column and the binate column.

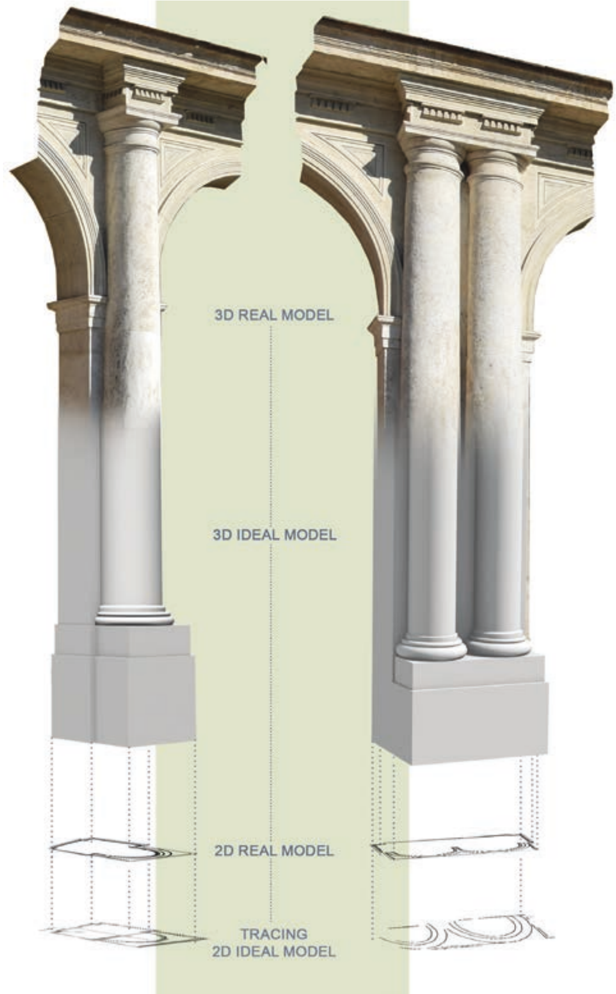

Figure 6. Construction of ideal 3D/2D models of the half column and the binate column. The information that could not be deduced from the worksite tracings are integrated with the images of the real elements.

a meter and a half from the surface. The parameters obtained made it possible to generate a legible model at 1:50 scale.[7]

The problem of scale has become decisive in surveying worksite drawings: pouncing made possible the acquisition of data at 1:1 scale, whereas the restitution scale of the mathematical model depends on the quantity of information contained in the incision. This seems to be a peculiar problem of this subject: the choice of the scale of the model is a function of the objectives to be achieved, but simultaneously this very choice depends the acquisition (of which adequate methodologies take advantage). It follows that for some architectonic elements represented by the incisions, the 3D reconstruction proves to be complete and corresponds to the information recovered from the tracing. This is precisely the case of the mathematical model of a coupled column (Incision 1): the signs of the tracing correctly represent all the mouldings and, consequently, the realized model contains all the information necessary to carry out a typological and stylistic analysis. In other cases, 3D modeling rested on reconstruction hypotheses and data integration starting with other incisions. We refer here to the model of the half column on the pillar (Incision 3) for which the information gained from the survey proved to be partial (according to the authors' interpretation of the incision 3, it represents three diameters of a column, they could refer to the sommoscapo, the entasis and the imoscapo; in the same incision, mouldings at the base of the column

7 The scale of the model depends on the quantity of graphic information it contains as well as on representation quality. In the field of digital photogrammetric processes, the parameters that determine the scale are the following: focal length and the distance of the photographic image acquisition from the object.

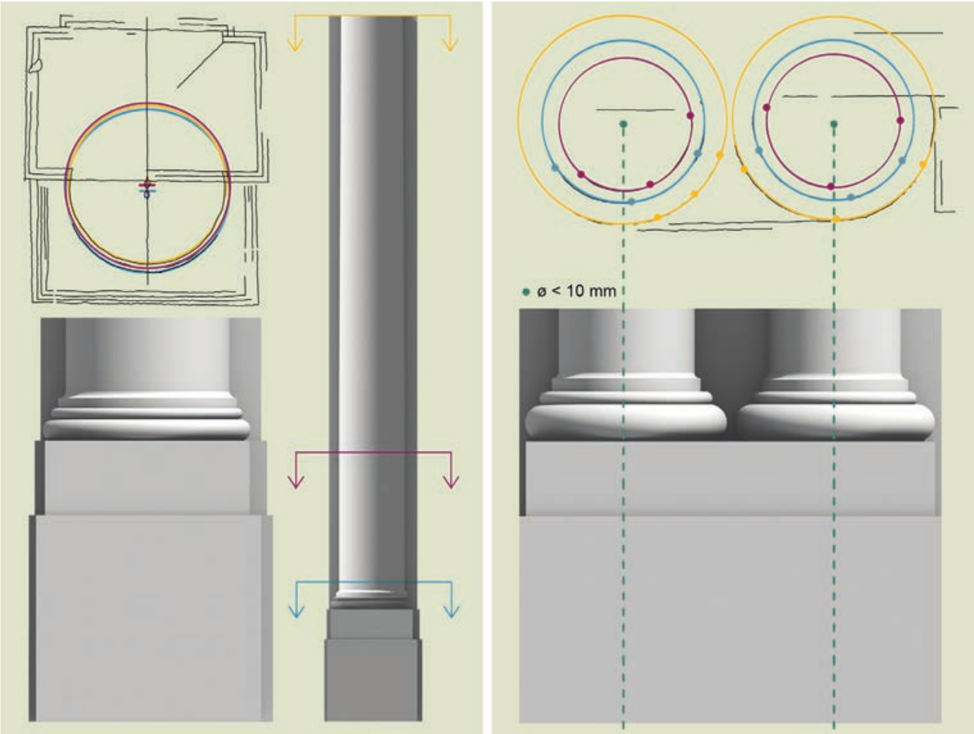

Figure 7. Analysis and geometric constructions of the half column and the binate column. For half column, the mouldings have been modeled on the basis of the surveying of the real element and of the tracing 5, since it is not possible to obtain enough information just from the worksite tracing 3.

are not represented). In these circumstances, the data were integrated with the information obtained from the adjacent drawing (Incision 5) contributing considerably to the construction of the model that would be topologically and formally complete (Figure 7).

Data Analysis: Real and Ideal Models

The stage of analysis was focused on comparing 2D ideal models with their corresponding real ones. The elaborated 2D and 3D models constituted the basis for the analyses of geometries and proportions. The analysis of the coupled column (Incision 1) revealed considerable differences between the ideal and the real model. The planimetric incised design shows three arches of circumference for both the coupled columns. Most likely, the arches correspond to the section of the column and of the mouldings represented in the projection. The two coupled incised columns are completely separate while the diameter of the shaft of the column appears to be reduced in proportion to the bases. Parts of the arches made it possible to construct diameters for three points. Their analysis demonstrated that all the centers, even though they do not coincide perfectly, are included in all the diameters shorter than 1 cm. The numeric model demonstrates the fusion of the two coupled columns in harmony with the lower moulding. The upper mouldings are adjacent while the shafts of the columns are brought closer to each other. What is more, the study of the horizontal section of the numeric model have diagnosed a flattening of the lower moulding in relation to the arch of the ideal circumference. The comparison of the coupled column represented through a survey with the column as realized showed no correspondence between the two elements.

The same kind of analysis was conducted on the other blueprints, and the comparison of real and ideal models yielded different results. The representations in elevation of the column shaft and of a part of the capital (Incision 2) proves to be similar to the one built for the porch. The analysis was conducted comparing both the real and ideal 2D models and verifying that the proportions between elements were equivalent. The column depicted lies on a horizontal axis, it is remarkable that the distance between the jamb of the church left door and the tracing of the capital perfectly corresponds to the total length of the built column shaft (Figure 8). This probably means that they used an architectural element – the jamb of the door – as a point zero of their tracing.

Regarding the single half-column (Incision 3), three arches of circumference are recognizable. This is probably a representation of the diameter of the

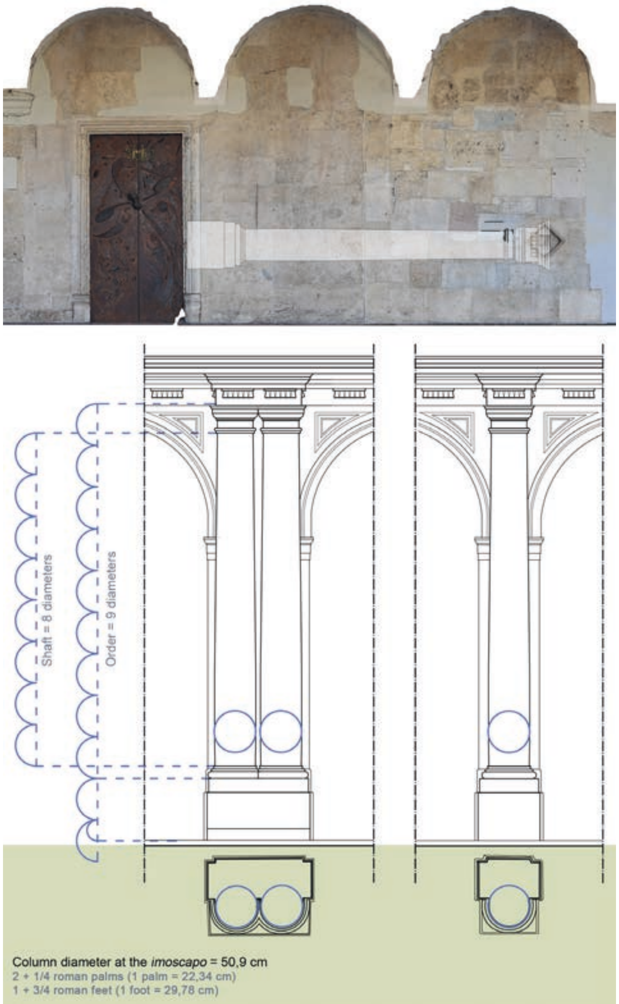

Figure 8. Proportion of the architectural order. The half column and the binate column. The total length of the order matches the distance between tracing 2 and the jamb of the left door of the church.

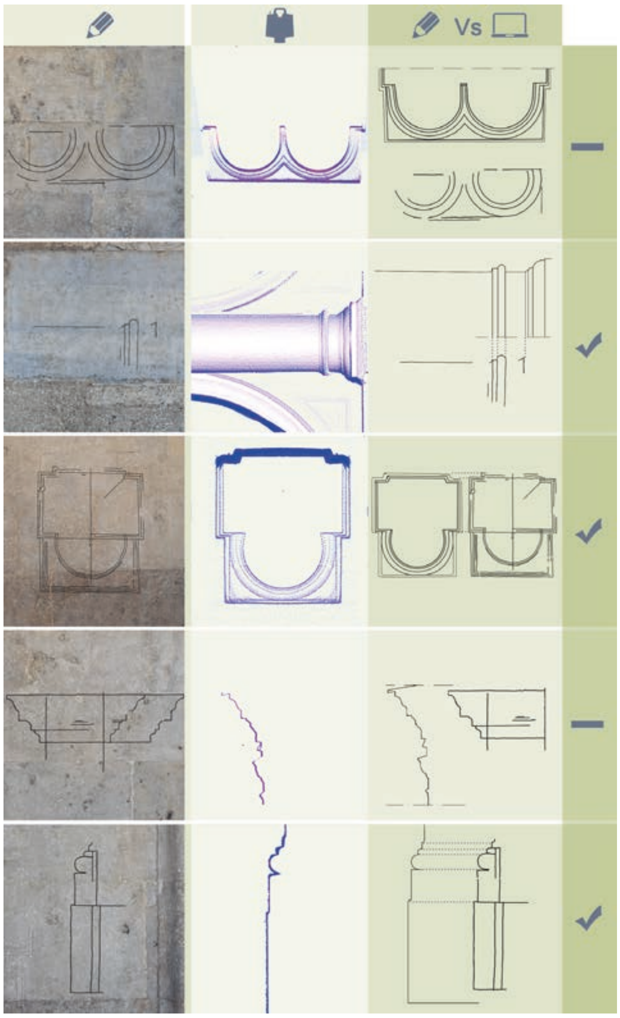

Figure 9. Comparison between real models and ideal models.

column at sommscapo, at the height of the entasis and the imoscapo. The incision is likely to have been realized on the basis of two rotation centers: the semi-circumference of the imoscapo seems to be off center in relation to that of the entasis and the sommoscapo. This evaluation is confirmed by two profound gaps in the stone which correspond to the two identified centers. A comparison with the numeric model of the real element confirmed the initial hypothesis: the diameters of the sommoscapo, the entasis and the imoscapo are comparable with those represented in the incision. The established correspondence between the two elements leaves no doubt that the incision represents the model of the semi-column realized at scale 1:1.

Conversely, in the case of the entablature (Incision 4), the built element does not completely fit the drawing. Recognizable on the incision are different solutions for the trabeation, some of which are incomplete. The axis of vertical symmetry has also been retraced. The drawing of the column base (Incision 5) is probably connected to the one illustrating a plan of the same architectural element (Incision 3). Mouldings of the base match the built ones in terms of category, dimension, and proportion. The information obtained suggested a comparison – in terms of proportions – first with the half column and then with the whole portico. The diameter of the single and the twin-column of the portico at its imoscapo amounts to 50.9 cm (Figure 9).

Verification procedure is being carried out to identify the unit of measure applied for sizing the diameter of the column. The diameter was used as a basis for the metrological-proportional study of the

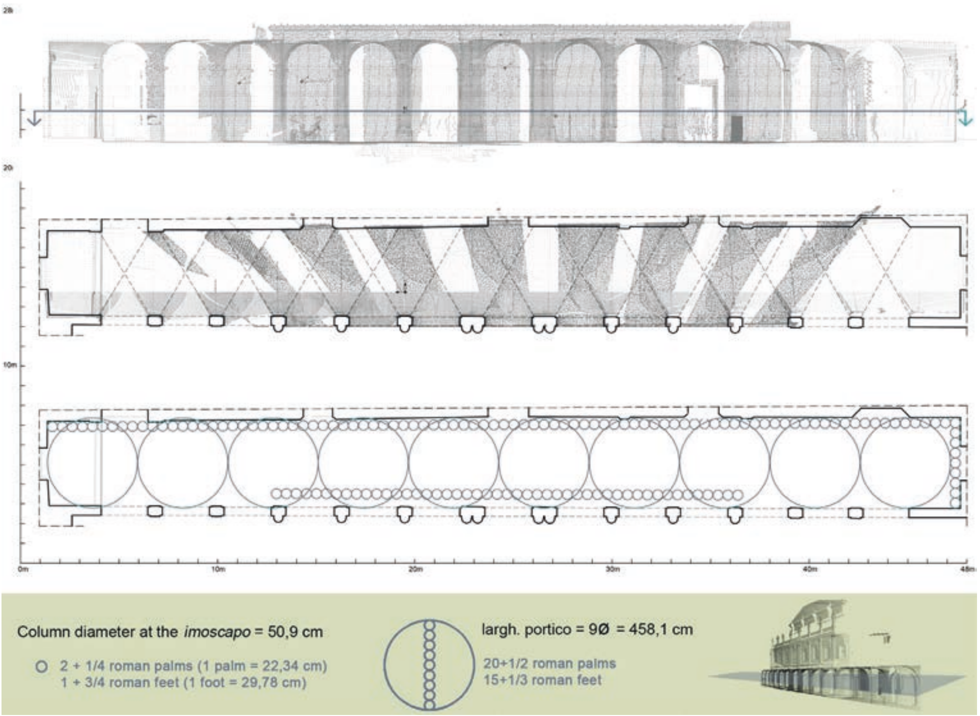

Figure 10. Proportion of the portico. The length, 46.31 m, corresponds to 91 modules; the width, which varies between 4.27 m on the left and 4.61 m on the right, completely match 9 modules in the central part of the facade, axis with the main portal.

portico to investigate the current formal appearance (Figure 10). The value is consistent with the structure sizing: the ratio between the sides of the façade is about 1/10, the one between the façade and counter façade by just over 1/2.

Conclusions

The analysis of the worksite drawings is complex because of the need to correctly interpret them. Often, even when just partially preserved, they are the only trace of documentation at our disposal. It requires an effort to abstract the signs and to interpret the design idea behind the construction, which not always corresponds to the existing constructed element.

All these activities prove to be strictly connected with the methodologies that aid cognition, documentation, and communication of cultural heritage through the interaction of acquired data and the elaboration of 2D and 3D models (which are increasingly more complete and complex). The procedures of the study constitute the basis for a methodology that can be applied in different contexts, from the verification of studies as to the adequate formal correspondence between real and ideal models to the verification of a possible relationship between incised representations and architectural models even when this association is not direct or immediate. It was made possible by the processes of model construction and the subsequent metric, geometric, formal, and stylistic study indispensable for extending the level of cognition (knowledge), ever more connected with the possibilities to archive, communicate, and spread the information on cultural artefacts, and also for their protection and preservation. A significant surplus value emerges from the approach that integrates competences of architects, art historians, and archaeologists. It has made it possible to catalogue Romanesque and Gothic incised drawings, to analyze their practical application in building, as well as to study the relations obtained between worksite drawings and the realization of architectonic elements by constructing and comparing real and ideal models.

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3D Digital Modelling and Digital History: A Methodology for Studying the Processes of Transformation of Nubian Temples and Landscape at the Lake Nasser Site

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Abstract

3D models are not only visualization and dissemination outcomes, but can be used to digitally collect, organize and visualize data starting from heterogeneous historical documents. In particular in this research 3D models are conceived to study the transformations of the sites along the river Nile now submerged by the Lake Nasser and the salvage of the temples. This paper illustrates the preliminary results and the issues about the use of 3D digital models to study the landscape and the temples before and after the construction of the Big Aswan Dam. The first results show that the discrepancy between the homogeneity of data required to build the 3D model and the non-homogeneity of historical documents is at the same time the weakness and the strength of the method, since it forces to explore new hypothesis and a proper use of paradata to manage the reliability of historical data.

Keywords: 3D modelling, 3D digital landscape, Nubian temples, digital history

Introduction

Models are one of the principal instruments of modern science (e.g., Frigg and Hartmann 2012). Among the different types of models used in science, the 3D models commonly used in architectural studies belong to the type of models based on analogy (Hesse 1966). 3D digital models are particularly powerful tools for the study and comprehension of historical sites and buildings, because, as underlined by Maldonado (1992), digital models allow a richer and more controlled interaction between user and model.

For this reason, 3D digital models, and the creation process of such models, are useful tools in the field of digital history. Historical research can be represented in a digital environment by visualizing relationships between buildings and sites, landscape details and changes. 3D models and virtual reality are commonly used to investigate the state of a building but can also be powerful tools to illustrate historical processes, a fundamental focus of digital history. The science of representation is of fundamental importance in achieving this as stated by Simon (1969) many years ago. The notion of substituting a process description for a state description of nature has played a central role in the development of modern science, and the description of a complex structure requires the right representation. 3D digital models are useful tools not only for state description but also for process description, in order to investigate how a historical building or site was conceived, used, modified, ruined or rebuilt; in other words, the physical and cultural phenomena that have characterized its life.

This paper illustrates the first results and difficulties related to the use of 3D digital models to study the historic transformations of the sites along the Nile river in the 20th century, before and after they were submerged by the waters of Lake Nasser. The research is conducted within an ongoing project entitled Cultural Heritage in Context: Digital Technologies for Humanities, carried out by a multidisciplinary team from the Department of Architecture and Design of the Politecnico di Torino and from the Department of Near Eastern Languages and Cultures of the University of California, Los Angeles (UCLA). The long-term project aim as a whole is to explore the possibility of developing a 3D virtual reality environment to recreate the drowned cultural landscape of Egyptian Nubia. In particular the aim of the very first part of the project discussed in this paper is to investigate the feasibility - as well a suitable methodology - of creating digital models of buildings and sites from the available historical documents and maps. From a long-term perspective, this paper is addressed to scholars as a resource for further research, as well as a way to convey narratives about the changing landscape of this region. More specifically, the first part of the project outlined here is geared towards the instruction of architecture students. The project is based on integrated and multidisciplinary approaches in archaeology and cultural heritage, and on the use of digital data processing and management.

Overview

Between 1960 and 1980, the Egyptian Nubia, defined as the area of the Nile Valley between the first and second cataracts, was deeply transformed by the construction of the Aswan High Dam, the flooding of a huge part of the territory, and the displacement of the main temples during the international campaign carried out by UNESCO (Säve-Söderbergh 1992; Tamborrino and Wendrich 2017). The scale of flooding provoked by the construction of Aswan High Dam was unprecedented and was the cause of a huge environmental change in the Nile region with the creation of Lake Nasser. Because of the dam, a large territory changed forever. The age-old structure of the river Nile and the relations of the people in its valley were transformed by the lake that was created and by the people and monuments that had to be evacuated.

This was a multi-scalar disaster that can be analyzed using a multi-scalar process for studying and visualizing historical changes related to the event. Digital Humanities methodologies have created new perspectives for historical research. Documentation can be collected into digital datasets which allow for the management of a new quantity of data. Data can be spatialized and modeled in new ways, presenting all the information recorded in written texts, historical cartography, and iconographic sources in spatial-temporal settings, in order to recreate a new scenario of understanding. In the case of a catastrophe, how to represent historical research by visualizing the dynamics of change is especially relevant. This approach can allow the recreation in VR of the landscape before the catastrophe in order to recreate a rich framework of information for a better understanding of the relationships between the monuments and the context. It is particularly effective in the case of archaeological remains where 3D models allow the reconstruction of ancient fragments.

The possibility of effective use of 3D models is related to the reliability of the model. Such issues are addressed by the London Charter for the Computer-based Visualization of Cultural Heritage, that focuses on paradata to provide information on the human processes of understanding and interpretation of data objects. For this reason, the London Charter underlines the fundamental importance of the Documentation Process: documentation of the evaluative, analytical, deductive, interpretative and creative decisions made in the course of computer-based visualizations should be disseminated in such a way that the relationship between research sources, implicit knowledge, explicit reasoning, and visualization-based outcomes can be understood (Denard 2012). Some approaches have been developed over the last decade to disclose the knowledge and research claims made with virtual environments, such as the annotation system developed for VSim, a software prototype for interacting with 3D computer models in educational settings that we are using in this research (Snyder 2014).

Methodology

This paper focuses on the description of the methodology used to create 3D models of the landscape and temples starting from historical documents. This is part of a wider process that comprises the historical research involved in the UNESCO Campaign, the digital processing of historical data and the conceiving of a new storytelling format for the campaign; the whole process is described here in brief, in order to provide a useful background, while the whole project will be published upon its completion.

Figure 1. View of the 3D model of the site of Abu Simbel temple, before and after the displacement of the temple: on the left, the original site along the Nile, on the right, the new site on the shore of the Lake Nasser.

In this research, 3D models are used as a tool to collect, organize and visualize data starting from heterogeneous historical documents. 3D models are conceived and used to study the transformations of the landscape, including urban settlements and temples before and after the flooding following the construction of the Aswan High Dam.

The digital modelling activity aims to produce some computer-based outcomes:

- a 3D digital model of the portion of the Nile valley that was submerged by the flooding, before and after the disaster,
- digital models of all the temples that were saved by displacing them during the UNESCO campaign

Multidisciplinary Approach and Composition of the Research Team

Given the project's complexity, it requires a multidisciplinary approach. For this reason, the team is composed of researchers from different disciplines: the History of Architecture, Digital Modelling, Representation of Architecture, Egyptian Archaeology, and the Digital Humanities. In order to process the huge number of historical documents and to build the 3D models of all of the 15 temples saved in the UNESCO campaign, 70 students attending the Master of Science in Architecture for Heritage Preservation and Enhancement at the Politecnico di Torino were involved under the supervision of members of the research team.

Delimitation of the Study Area of the Case Study

The area of interest is the area along the river Nile that is now submerged by the waters of Lake Nasser, between the first and the second cataract of the Nile, and in particular between the Aswan Dam in the north and the temple of Abu Simbel in the south (Figure 1). The distance between the two sites is approximately 280 km measured following the course of the Nile. The area housed many 20th century villages, with thousands of buildings, that have been submerged, and 15 major Egyptian temples that were saved by relocating them to higher ground or to foreign countries.

The model of the terrain covers a surface which is approximately 4 km wide and runs symmetrically along the axis of the ancient River Nile before the flooding (the delimitation of the ancient river Nile is based on the survey carried out in 1959 before the construction of the Aswan High Dam). This surface follows the axis of the River Nile from the first Aswan Dam in the north to 20 km south-west of the site of Abu Simbel. In the case of the temples relocated to foreign countries, the new sites – museums or urban spaces - are modeled too.

Delimitation of the Time Range of Interestt

The research and consequently the modelling focus on the transformation of the landscape and of the cultural heritage due to the creation of Lake Nasser and the UNESCO Campaign for the salvage of the main temples of Nubia. The UNESCO campaign was launched in 1960 (UNESCO 1960) and was completed in the 1980s. For the temples that are near the Aswan dams, such as Philae (Figure 2), the time range needs to be extended because they were partially flooded as a consequence of the construction of the first Aswan Dam in 1902. As a result, and as a general rule, the digital modelling regards the construction of 3D models of buildings and sites ranging from the late 19th century to the late 20th century. In the case of some temples, if data are available and where they help understand the transformation process, 3D models of other and more ancient diachronic phases were also created.

Figure 2. Three frames of a video clip that shows a virtual reconstruction of the potential submersion of the temple of Philae due to the construction of the Aswan High Dam (3D digital model by Del Fabro M., Marchisio V. and Zanardo E.).

Input Data

3D models are developed starting from historical documents. Only in the case of the Temple of Ellesija, currently in the Egyptian Museum of Turin, was a photogrammetric survey carried out. The input data used for the construction of the 3D model of the terrain come from various historical cartographical sources, particularly the drafts of an aero-photogrammetric survey carried out in 1959 as part of a UNESCO campaign, on a scale of 1:10,000 (IGN 1959), and maps on a scale of 1:250,000 printed in 1958-1960 by the US Army.

The input data for the construction of the 3D models of the temples are very heterogeneous, with differing levels of reliability. These include descriptions and drawings by early travelers from the 18th and 19th centuries, surveys by architects, excavation reports published by archaeologists, topographical maps from the surveys done in the early 20th century, early photographs and films from the 1960s, and the documentation collected by UNESCO (Tamborrino and Wendrich 2017). As a consequence, according to the wealth of information and reliability of the historical documents, the level of detail of the digital models of every single temple is non-homogeneous and depends on the type of historical documents available.

Level of Detail

The digital modelling methodology is based on a multi-scalar approach: the level of detail, the scale of representation, the extent of the model, the content of the model, and the precision of modelling are optimized for every phase, as are the input data, the modelling software, and other digital tools.

The multi-scalar modelling methodology is based on three phases and levels, that correspond to three rising scales of representation, with the level of detail increasing from the first to the third level:

- Level 1 – territory: 3D modelling of the Nile Valley before the displacement of the temples;
- Level 2 – the building context: 3D modelling of the temples in their original context;
- Level 3 – building subsystems: building information models and/or more detailed 3D models of parts of the temples.

The result of these three levels of modelling is the creation of 2D and 3D content suitable for building a comprehensive multilayered model and multimedia products - animations and simulations - both for research and dissemination purposes.

Subdivision of the Modelling Process in Different Phases

The modelling process is subdivided into three main phases that correspond to the three levels of detail previously described.

Level/Phase 1: 3D Modelling of the Nile Valley before the Flooding | As mentioned above, the 3D model of the state of the Nile Valley before the flooding is based on various historical cartographical sources, particularly the drafts of the aero-photogrammetric survey carried out in 1959 and the maps printed in 1958-1960 by the US Army. The 1959 aero-photogrammetric survey covers an area measuring approximately 4 km wide, running symmetrically along the axis of the ancient River Nile before the flooding from Aswan in the north to 20 km south-west of the site of Abu Simbel. It is printed on 41

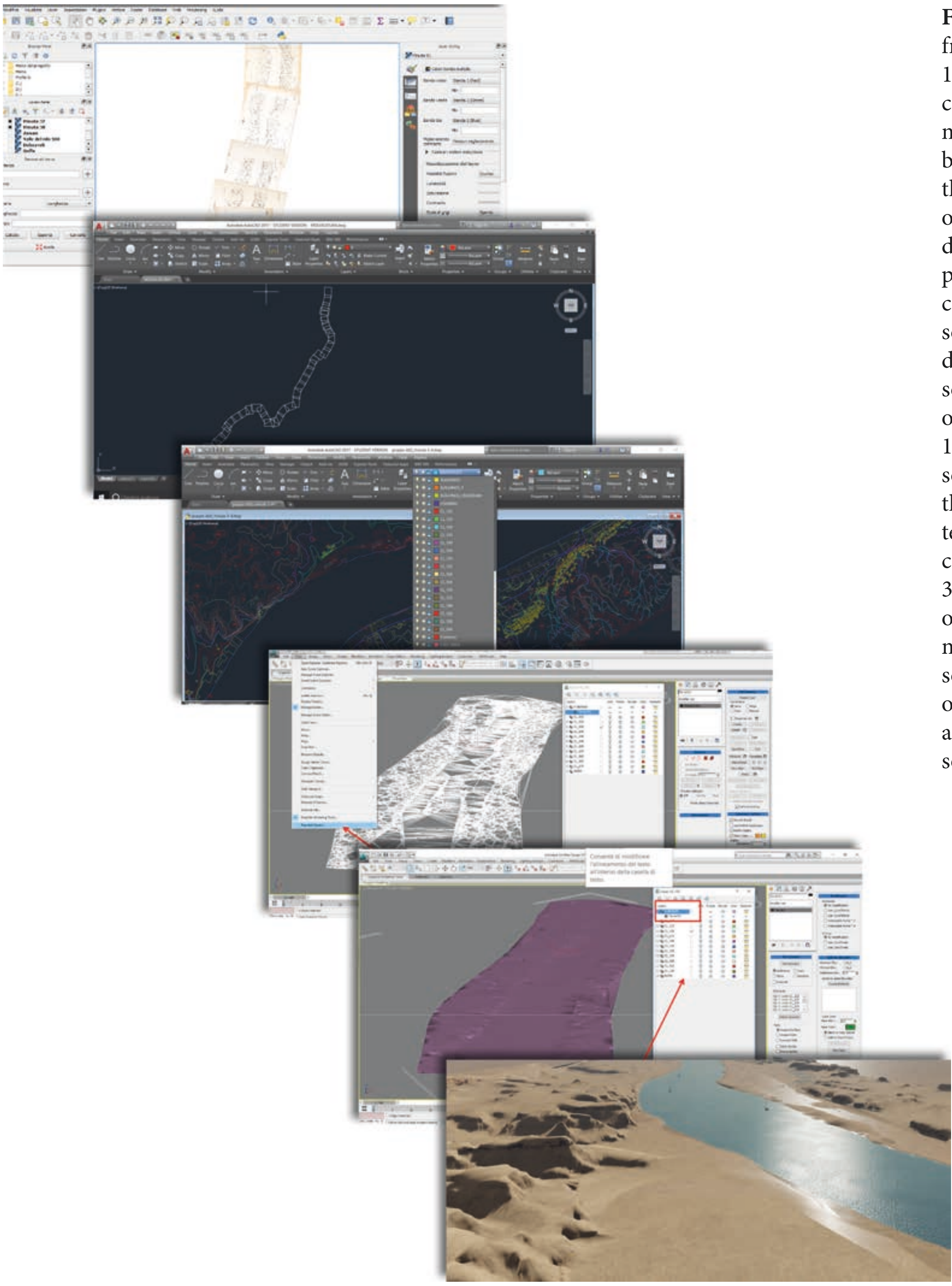

Figure 3. Screenshots from the Level/Phase 1 concerning the construction of the 3D model of the Nile Valley before the flooding. From the top: georeferencing of 41 sheets of the draft of the aero-photogrammetric survey carried out in 1959 (QGIS software); export for digitalization (AutoCAD software); digitalization of one of the 41 sheets of the 1959 survey (AutoCAD software); creation of the mesh surface of the terrain starting from contour lines (Autodesk 3DS Max software); optimization of a quad mesh (Populate Terrain software); refinement of the terrain model and rendering (Lumion software).

sheets, numbered starting from the south; but there is a small gap (a section measuring approximately 3.5 kilometers long) between sheet number 28 and sheet number 29. In the 1959 aero-photogrammetric survey, the topographic surface of the terrain below the elevation of 182 meters is described through elevation points and contour lines every 10 meters and some auxiliary contour lines every 5 meters. The portion of the map above the elevation of 182 meters, the area that was not to be flooded by the dam, is only described using contour points (with the exception of sheet number 21, where 10 m contour lines are used above the elevation of 182 meters) (Figure 3).

In order to produce the 3D model of the terrain, three tasks were performed. Task 1.1 involved the georeferencing of maps. This was done with open source QGIS software. The georeferenced maps were then exported into AutoCAD for the digitalization. Task 1.2 was the digitalization of maps. The digitalization was mainly carried out on the 1:10,000 scale

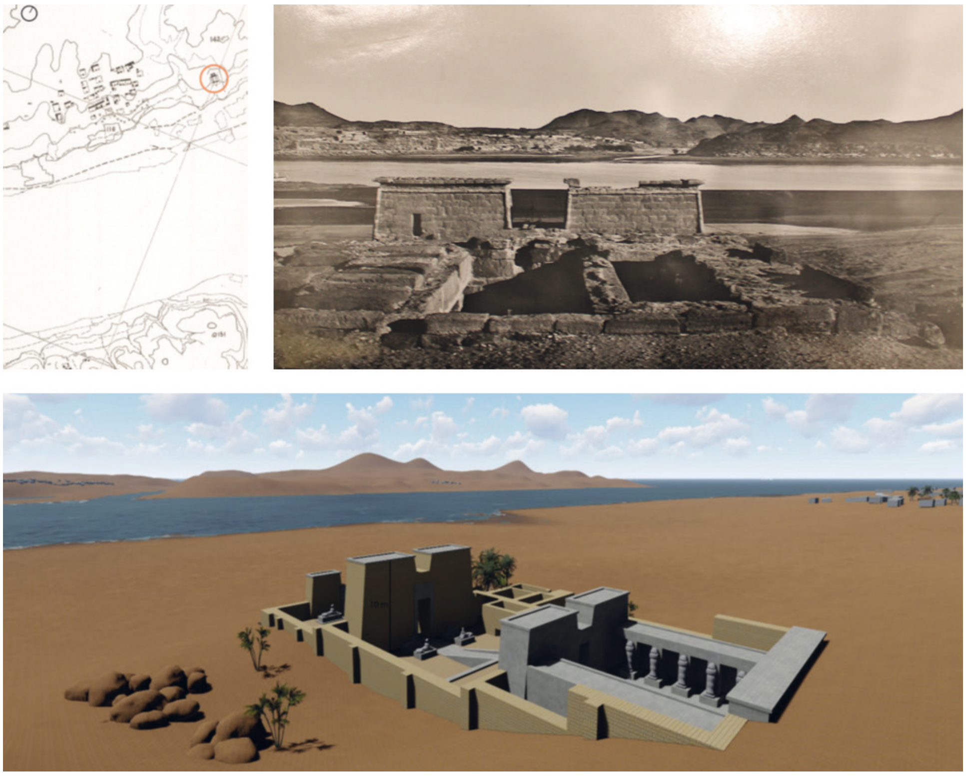

Figure 4. Identification of the original position of the temple and 3D reconstruction of the Temple of Wadi al Sebua and of the adjacent terrain features on the basis of maps and historical documents.

maps. We used the 1:250,000 maps to integrate the missing parts. The missing parts belong to three categories: the area between sheet numbers 28 and 29, the area between the ancient dam of 1902 and the new dam not covered by the 1959 survey, which corresponds to the area of the Temple of Philae, and the contour lines above the 182-meter elevation. The final task in this phase (Task 1.3) was the generation of the 3D surface of terrain based on contour lines. The generation of the mesh surface of the terrain is based on the digitalization of the contour lines. The surface of the terrain higher than 182 m above sea level that is missing in the 1959 survey was obtained starting from the contour lines of the US Army map (interval 50 meters) and from elevation points. The mesh surface is generated with the software Autodesk 3DStudioMax release 14 and the scripted plug-in Populate Terrain that allows the creation and optimization of a quad based surface that can later be remodeled using push-pull painting for example.

Level/Phase 2: 3D Modelling of the Temples in their Original Context before the Flooding | This phase was carried out in two tasks. The detection of the original position of temples on the scale 1:10,000 maps, when possible, consisted of Task 2.1 in Phase 2. The documents from Centre d'Étude et de Documentation sur l'Ancienne Égypte (or CEDAE) in our possession record the geographical position of every temple, in some case with great precision, and in other cases with less accuracy. For this reason in some cases this task was easy (for example the site of the Ellesija temple is precisely recorded), while in other cases the most precise information regarding the geographical position was the number of the map, and in such cases the detection of the exact original position of temples was carried out with a careful reading of the maps and other documents such as photos and paintings.

The second task (Task 2.2) consisted of creating the 3D preliminary models of the temples and of the adjacent contexts on the basis of maps and archival documents (Figure 4). The main elements of the modeled context are terrain, villages, and vegetation. The terrain model obtained in the previous task is refined using historical imagery where this exists (the quad based surface can be remodeled using push-pull painting for example). Currently the villages are modeled on the basis of the 1959 survey but only in the areas near the main temples, as a further procedural modelling of the villages constitutes a future task of the project.

A more detailed modeling of the temples is performed in task 3.2 (see below) and then imported

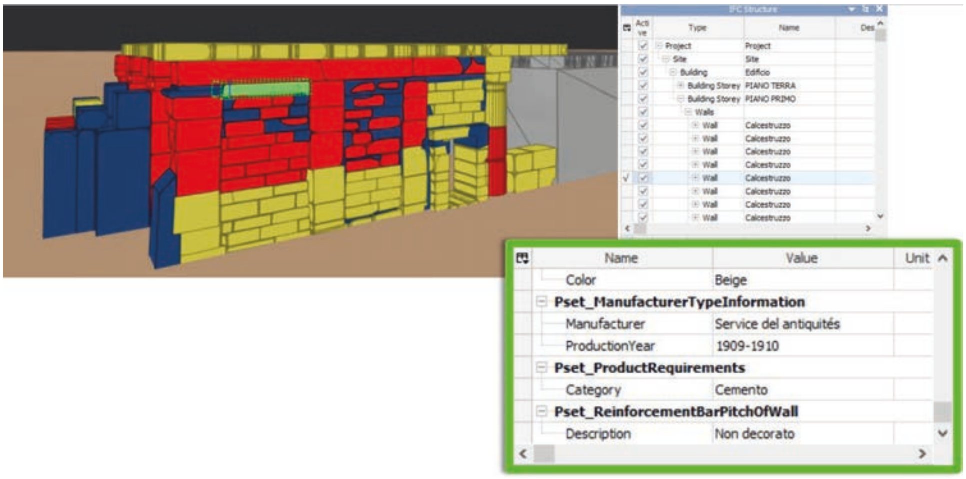

Figure 5. Building Information Modeling is used in order to associate additional information, such as alphanumeric data (e.g. date, material, state of degradation, management of restoration, etc.) or other files (e.g. images, archival documents, etc.) to building components. In this case, the BIM model of the Temple of Amada (Archicad 20 and IFC Viewer BIM Vision software).

into the model of the site. In this phase the input data are not homogeneous for all 15 temples, nor is the modelling strategy homogeneous. While the starting point is the same for all the temples, the terrain model created according to the UNESCO aero-photogrammetric survey, the refinement depends on the availability of the historical imagery, such as ancient photographs, paintings, or drawings. The modelling strategy for the site is approximately the same for all 15 temples: push/pull of the terrain grid, addition of textures, addition of vegetation features, addition of adjacent buildings, then rendering with the same Lumion software in order to ensure homogeneity of the rendering parameters. The reliability, however, is not homogeneous, due to many factors. The variable availability of historical imagery impacts reliability along with the fact some imagery, particularly paintings and drawings, is strongly affected by the subjectivity and cultural period of the author or artist. Historical illustrations often show different kinds of optical deformations in order to enhance some particular aspect of the building, such as the alteration of some perspective parameters to deliberately give the illusion of bigger buildings, as demonstrated in Figure 10 below. Last but not least, the interpretation of the historical imagery (such as the interpretation of the dimensions and distances of surrounding rocks) is affected by the subjectivity of the authors of the digital model, who are different for every one of the 15 temples.

Level/Phase 3: Detailed 3D Models of the Temples | This phase was carried out by completing two tasks. The 2D digital drawing according to historical documents and the scaling and digitalization of these archival documents comprised Task 3.1. As part of this task, the 2D digital drawings were overlaid on each other based on date in order to assess precision, reliability, and level of detail. The Level of Detail (LoD) is not homogeneous, according to the type and reliability of the historical documents.

Task 3.2 involved the detailed 3D modelling of the temple. 3D geometrical modelling was the standard method adopted to collect all the geometrical data from the historical documents; in some cases Building Information Modelling (BIM) was adopted in order to associate additional information, such as alphanumeric data (e.g. date, material, state of degradation, management of restoration, etc.) or other files (e.g. images, archival documents, etc.) to building components (Figure 5). The modelling strategy in this task is not homogeneous, as the input data, the nature and reliability of the historical imagery, and the features of the temples vary greatly. As a consequence, there was variability in the type of modelling, either geometrical model or BIM model, the level of detail, from modelling of the main features of the structure of the building only (basement, walls, doors, columns) to modelling the small details and building subsystems (decorations, constructive details, or even all the stones as unique elements), and the software employed, Autodesk 3DsMax and AutoCAD or Rhinoceros for geometric modelling or BIM Software (Autodesk Revit, Archicad).

Preliminary Results

The project is ongoing, but some preliminary results are evident. The first result is an original system of

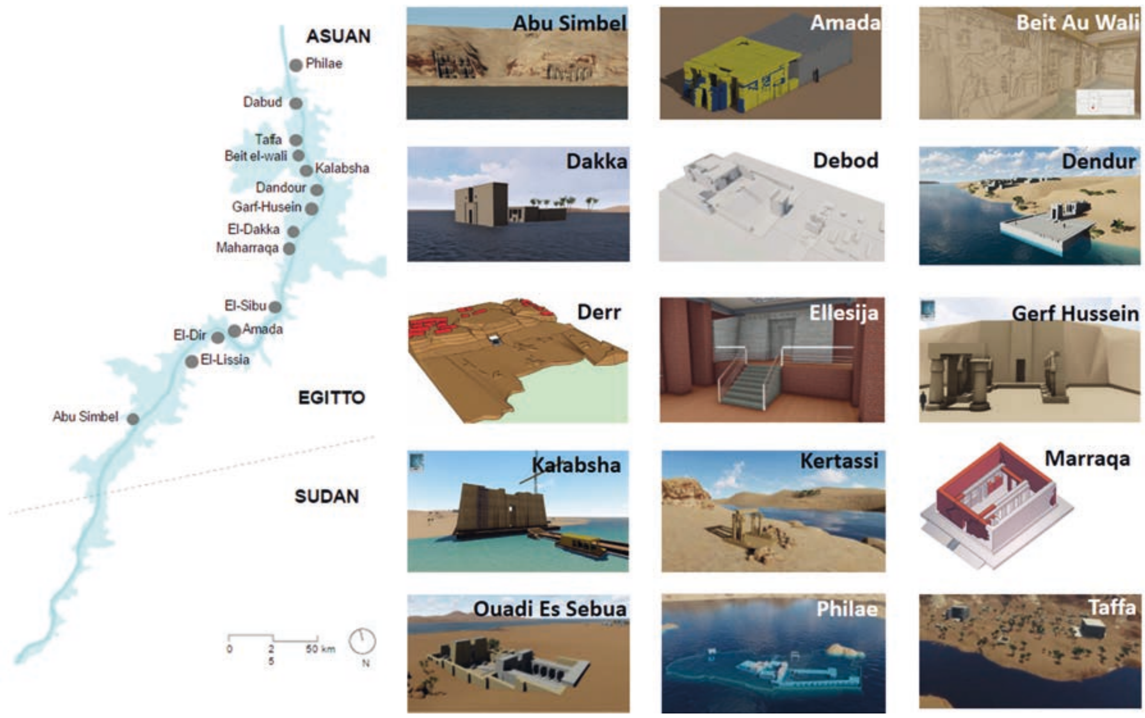

Figure 6. Cartographic elaboration of the area of the River Nile/Lake Nasser with the location of the 15 temples that were displaced, and a view of the model of each temple.

multi-scalar, 3D models of the Nubian area and temples. It is worth considering that, despite the existence of some systematic databases of 2D drawings (Fauerbach et al. 2010), before the start of the research project there was a great deal of uncertainty about the possibility of creating 3D models of every temple on the basis of archival documents only and about the level of detail obtainable for every site. That said, listed below are the preliminary digital tools, which will be improved in the second part of the project:

- 3D model of the terrain surface along the Nile, from Aswan to Abu Simbel, before the creation of Lake Nasser;
- 3D models of all 15 temples (building) and their sites (terrain, villages, and land cover) before and after the creation of Lake Nasser (Figure 6);
- a database of historic data, hypertext, and multimedia products – animations and simulations – of all 15 temples.

The importance of these preliminary results is as follows:

- the 3D model of the entire ancient valley of the Nile before the flooding is, as far as we know, attempted for the first time, and provides a homogeneous model of the 280 km long terrain surface;
- the models of the temples provide the first database of 3D models of all 15 temples. It is not completely homogeneous in terms of content and level of detail, but constitutes a strong starting point for further refinement and research;
- the digital models and the digital archive of historic documents constitute the basis for the creation of multimedia products – animations and simulations – of all 15 temples both for research and dissemination purposes.

3D models and the multimedia products are tools to improve knowledge in many ways, and in this project they are intended to improve our understanding of these buildings and their surrounding terrain as well the management of these places (Figures 7 and 8). As visualization tools, digital models and animations (through VR and videos) are commonly used

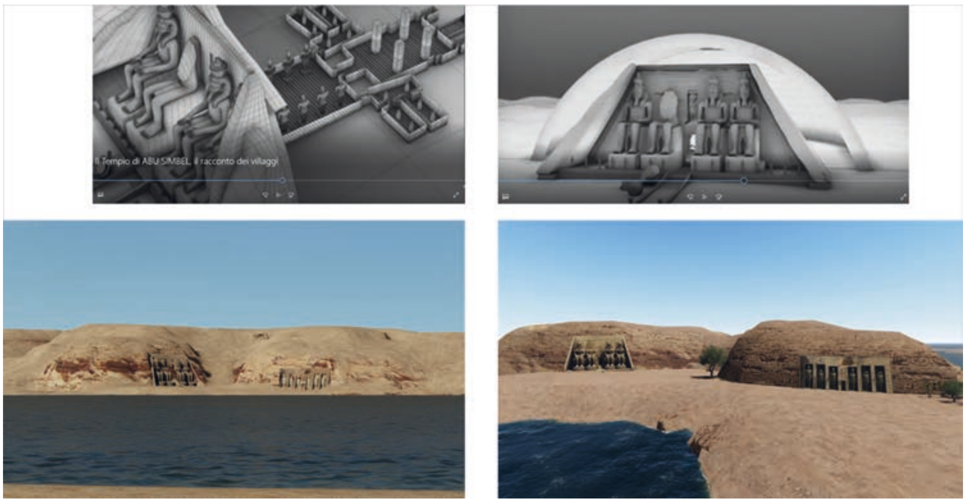

Figure 7. View of the structure and of the exterior of the temple of Abu Simbel before (on the left) and after (on the right) the displacement. The 3D model allows for views, such as exploded views or cutaways, that help the understanding of complex buildings, such as the temple carved in stone; the 3D model also allows the comparison of views of the temple in different diachronic states.

for dissemination purposes, because they constitute a user-friendly visualization tool for many categories of users (i.e. museums, web pages, and digital museums). In this project they are part of an educational program dedicated to architecture students in order to improve their understanding of aspects of the history of architecture. The results of the educational program (one or two videos and one or two hypertexts for every temple) will be revised in order to design further visualization tools to disseminate the final results of the research. A first test on a case study (temple of Dendur) was conducted with the prototype software VSim to develop an interactive and educational digital environment based on the 3D model, historical imagery, and videos (Figure 9). These 3D models are also being used to assess the reliability, precision or cultural background of sources. As a result, artefacts and distortions in historical paintings and engravings were discovered (Figure 10).

In terms of improving management, the use of Building Information Modelling allows the creation of models that can be enriched with information (see Figure 5). In this way the content of the model is not only geometric data but can be enriched with alphanumerical data, files, and links. The construction of BIM models was performed in some case studies (i.e., the temples of Amada and Gerf Hussein) when in possession of survey documentation with a good level of detail. A further application is going to be tested in a new project funded by Politecnico di Torino in collaboration with Museo Egizio di Torino.

3D Modelling as a System of Knowledge to Collect, Interpret, and Store Information

The first results show that the discrepancy between the homogeneity of data required to build the 3D model and the non-homogeneity of historical documents is both the weakness and the strength of the methods employed. This discrepancy forces researchers to explore new hypotheses and search new historic data, and forces students to understand and manage the reliability of historical documents. In conclusion, the research project aims to build an "open knowledge system of virtual models to study, manage, document, preserve, evaluate, and popularize cultural heritage linking the concept of representation to the concept of information and vice versa."

While our initial efforts have allowed us to create a digital environment for the visualization and study of the dramatic landscape transformations that resulted from the construction of the Aswan dam and the recovery strategies adopted to save the world heritage of the Nubian temples, future work is still necessary. In accordance with the Principles of Seville – an implementation of the London Charter in digital archaeology - the project underlines that "the environment, landscape or context associated with archaeological remains is as important as the ruin itself" (SEAV 2010). As a consequence of the strong connection between computer-based visualization and digital history, future work will be focused on materializing the principles of scientific transparency. To achieve scientific and academic rigor in this virtual

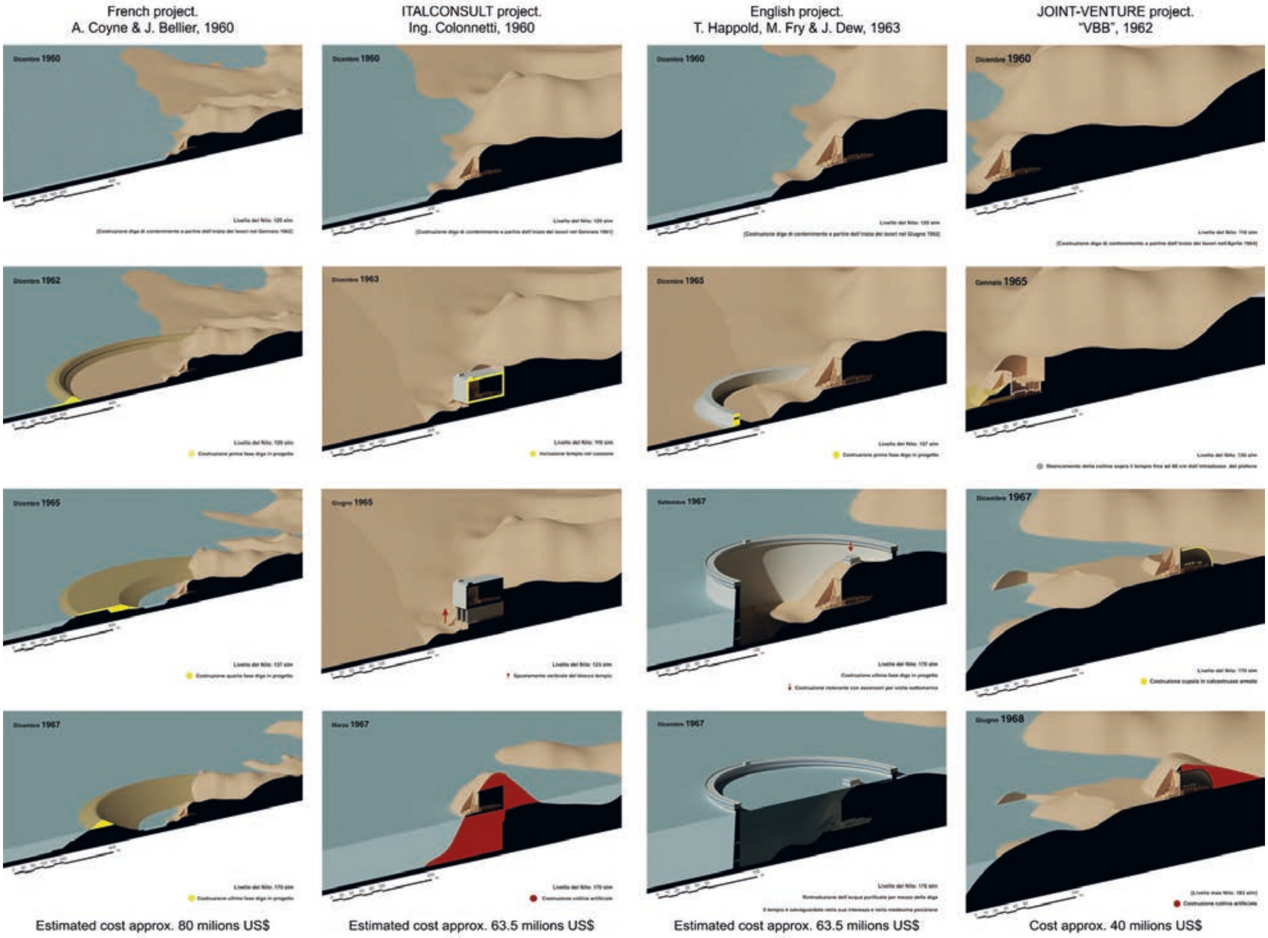

Figure 8. Graphic elaboration of the digital 3D reconstruction of four alternative projects for reducing the effects of the flooding in the case of the temple of Abu Simbel. Every column refers to a different design hypothesis, with progressive time phases. The reconstruction of digital 3D models allows the comparative visualization and study of the various alternative projects, by overcoming the graphical inhomogeneities of the historical documents. The comparative visualization is achieved by adopting homogeneous graphic standards: axonometric method of projection, identical relative position of plane and center of projection, congruent scale of reduction, similar level of detail, similar rendering lights and textures (3D models by P.E. Dalpiaz and G.M. Infortuna).

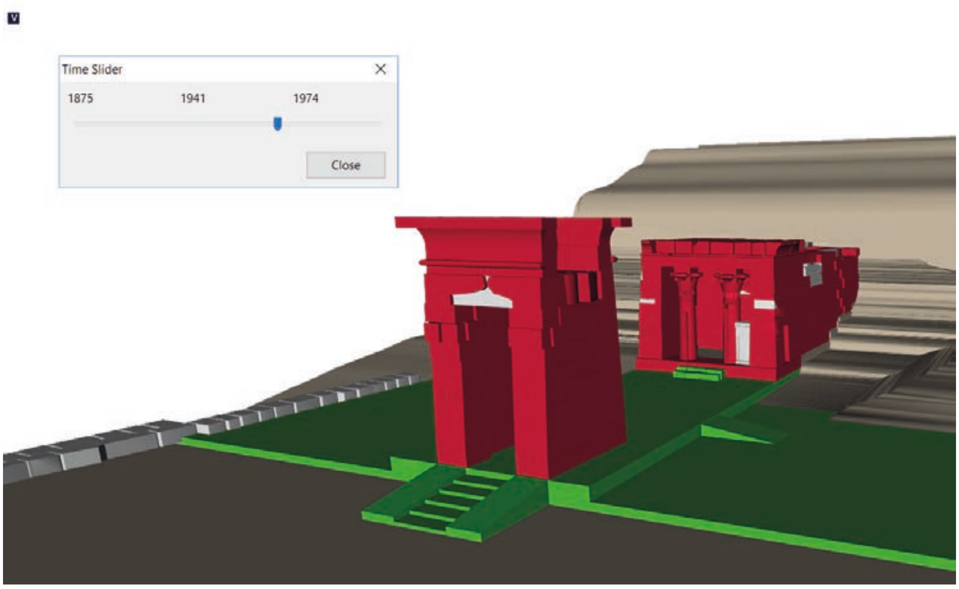

Figure 9. 3D model of the temple of Dendur in an interactive 3D environment with embedded resources, narratives and links to historical documents (software: Vsim prototype, under development at UCLA-IDRE (Institute for Digital Research and Education)).

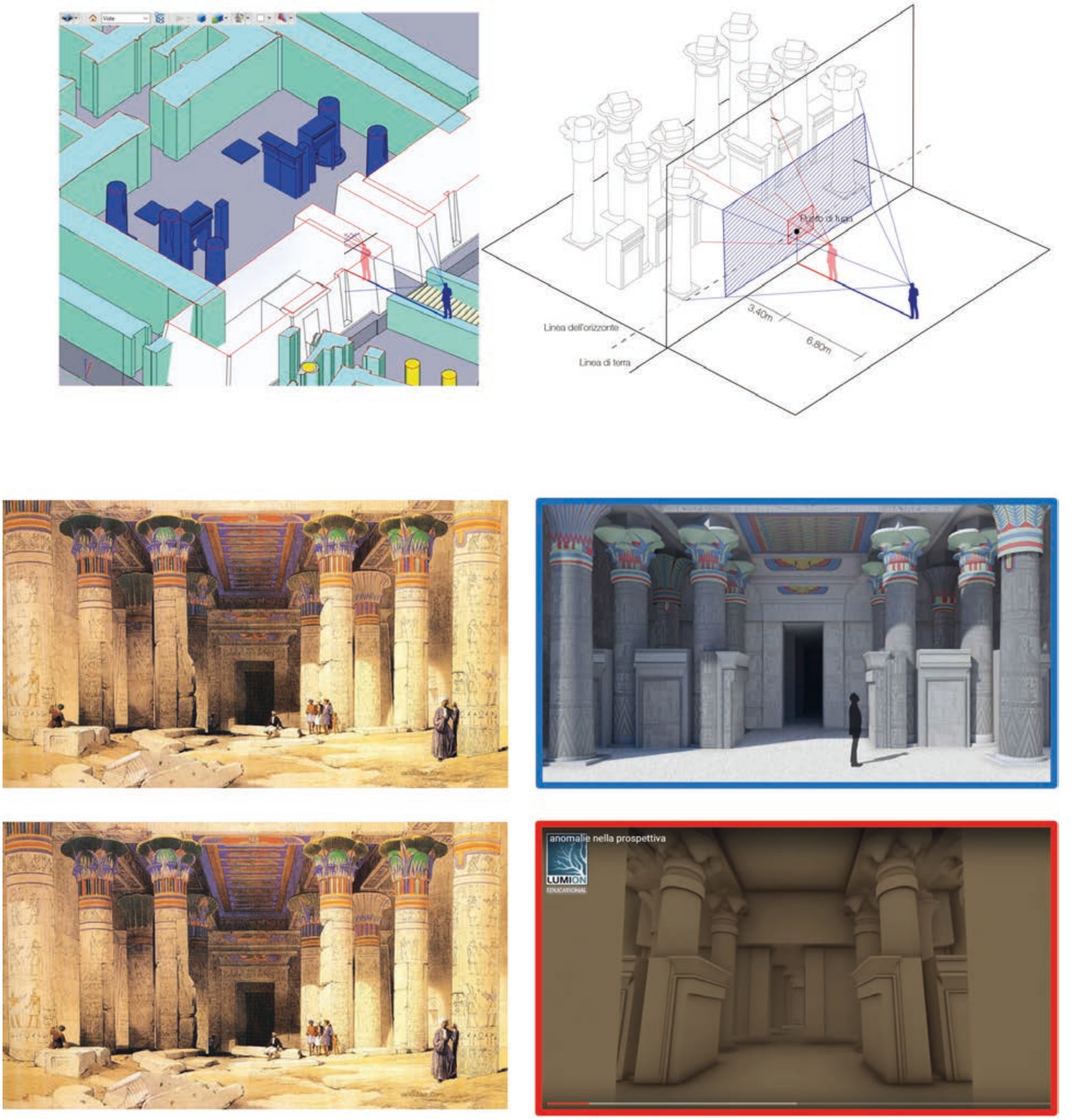

Figure 10. Example of use of 3D models to assess the reliability, precision or cultural background of sources. In this case, the 3D model is used to identify some perspective incongruences adopted by the painter David Roberts in this painting of the temple of Philae (1838) in order to emphasize the dimensions of the temple. The model is used in order to identify the point of view adopted in the painting (in blue), to verify that such point of view is not possible, as the view would be masked by the walls, and to compare the effect of the incorrect view with a plausible point of view (in red).

archaeology project, the intention is to prepare documentary bases to transparently present the entire work process: objectives, methodology, techniques, reasoning, origin, and characteristics of the sources of research, along with the project's results and conclusions. For this reason we are testing the adoption of software capable of incorporating metadata and paradata in 3D models (Procedural modelling for the villages, Building Information Modeling for the temples, Interactive 3D models with embedded resources such as hypertext and multimedia products and links to primary and secondary resources), as they are crucial to ensure scientific transparency.

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Parametric Representation of the Architectural Orders: Testing of Parametric Modelling for Simulation and Interpretation of Classical Architecture

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Abstract

The Architectural Orders have always occupied a key role in architectural doctrine. During the Renaissance, after the rediscovery of the Vitruvian text, each of the most famous architects gave their own interpretation of composition and proportion with respect to the Orders. After a careful analysis of some of the main treaties, it has been necessary to determine a unified interpretation of the genesis of the Orders and to create a single digital model that could be declinable in various versions. By advanced digital techniques, it was possible to generate a representative algorithm in a basic modifiable structure using different parameters. Results are also important due to the direct comparison between authors. The algorithms may also support accurate representations and interpretation of the actual artefact's shape, allowing us to hypothesize the author's style and, in case of restoration, to operate in a consistent way.

Keywords: Architectural Orders, heritage, modelling, Renaissance, restoration

Introduction

In architectural history, after the remarkable position in classical times and the subsequent oblivion of the Middle Ages, Renaissance architects rediscovered classical orders and their proportions. The tradition dates back to 1416, when, during the Council of Constance, a group of three scribes decided to go to the St. Gallo Monastery, where one of them, Cencio Rustico, found one of the most important publications in architectural history, the "De Architectura" by Vitruvius (Tiraboschi 1787).

However, during this period there was a sudden and great interest in the most well-known minds of the Renaissance, even in the humanities, in relation to the Vitruvian manuscript. More importance was given to Books IV and V of "De Architectura", where the description of the Architectural Orders is located. Consequently, the architectural orders and the classical proportions took off once more and started again to be a major element in architecture also due to the contemporary and increasing interest in archaeological sites. As a matter of common knowledge, the few drawings that Vitruvius attached to the manuscript were lost during medieval transcripts, due to the lack of drawing ability of the Benedictine monks. This difficulty combined with an unclear Latin language contributed to the birth of many different interpretations of the Architectural Orders. The architects who approached this doctrine elaborated personal theories that materialized with the creation of ever-changing artefacts and the writing of a multitude of great authors' treatises on this subject.

A detailed analysis of some of main Orders treaties, in particular the works of Vitruvius, Alberti, Vignola, and Palladio, highlighted the need to create a unified genesis of the Orders' interpretation so as to create a single model that could be applied to the different, well-known versions. Since survey is an important part of this process, the aim was to define a new way of representing the five orders that could be useful for the preservation of ancient artefacts.

Having basic, easy-to-modify models could speed up the stage of graphic restitution of real artefacts,

Figure 1. Rhinoceros and Grasshopper logos.

thus improving the heritage cataloguing system. This study could also be helpful in the critical survey phase. The possibility of having the representations of those models idealized by the treatises to compare with real cases, could allow for making assumptions about certain elements, like the author's identity and consequently getting, for example, information about the construction techniques used and the construction process of the entire studio. These data are fundamental in the case of restoration and consolidation of the analysed artefacts, enabling the design of an intervention that is as consistent as possible with the original identity of the work (Docci 2009).

The same process could be extended to a wide range of case studies. A series of factors may be investigated, such as the growth process of an urban centre, the use and development of different categories of buildings, the progress of construction techniques, and others.

The Instrument

The classical meaning of the term "Architectural Order" groups together the compositional and proportional rules named as Order and Symmetry, wherein elements are simultaneously dependent on the overall system and the individual parts. These notions define the orders for the algorithm and digital tools. Specifically, generative modelling seems to be the best way to reach the goal.

Normal 3D modelling allows for the creation of models which transmit only an image. This is measurable in all its parts but does not give any information about the graphics rules and the process used by the designer. However, the result of generative modelling is an element that contains various information. In addition to the traditional 3D image, the designer may also produce a representation of the generative algorithm, which could be considered a "representation of the representation".

The results of generative modelling are comparable to a treaty, as the model contains both the rules and the final object. Moreover, the algorithms could be continually adaptable and can evolve into countless new forms as a digital tool to create a family of objects with similar features (Davis et al. 2011). The models of this project have been developed with the software Grasshopper. Grasshopper is a Visual Scripting add-on developed for one of the most popular 3D modelling programs, Rhinoceros (Figure 1). In short, Grasshopper is a free scripting visual editor designed to make program knowledge unnecessary. Due to an intuitive graphic approach based on a knot interface, the users can develop a set of instructions that are translated into a 3D model in the Rhino window.

The algorithm is a way of troubleshooting, to compute a path leading to the final solution from the question and the initial information. The process of the algorithm leads to a set of instructions that when repeated (always with the same input data) give the same result (Tedeschi 2010). The Grasshopper algorithms (Figure 2) are like a knots diagram where every knot is an operation that matches a geometry only after the application of input parameters. In the Rhino interface, the operation could be linked to others, creating a web of mutually dependent operations. Changing one of the inputs gives a different result and a different geometry, known as "Parametric Modelling." That is why, once the five Orders algorithm was designed, it has not been difficult to translate it into the different authors' versions. The possibility to define a general procedure has resulted in a common genesis for the Orders, and at the same time allows for the determination of the main differences.

The Orders' General Rules

This project studied the following Orders' Treaties: the "De Architectura" by Vitruvius, the "De re aedificatoria" by Alberti, the "La regola delli cinque ordini d'Architettura" by Vignola, and the "I quattro libri dell'Architettura" by Palladio. The aim was to give general rules regarding proportions within the architectural orders. Starting from their works, it could be quite easy to find the thickness and the ledge of every part. The column diameter at the bottom is the key measurement and determines all the other dimen-

Figure 2. Algorithm view in Grasshopper.

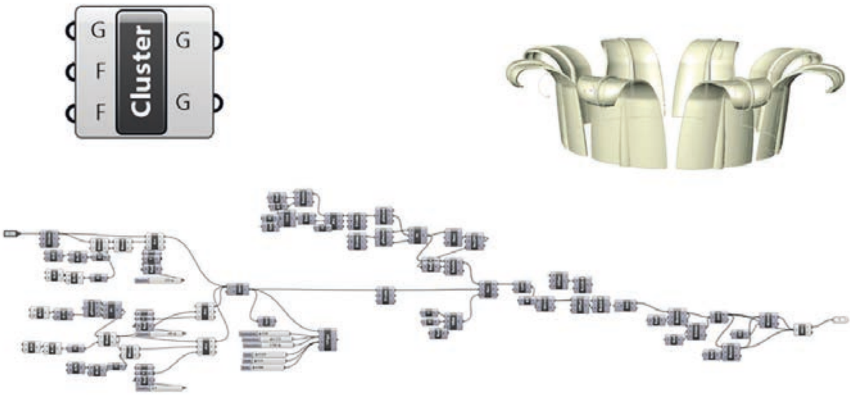

Figure 3. Column models from Vignola.

sions. Such a practice allows the designer to make a representation unlinked to the metric system used. This is the idea that has always charmed architects.

The rules of proportion could be summed up in three different groups: 1) the following partitions process; 2) the submultiples process; 3) the decimal metric process.

The first process takes every dimension from the previous ones, used by Vitruvius, Alberti and Palladio. This process has considerable benefits in the context of hand drawing and considering the elements final shape. The submultiples process, used by Vignola, divides the radius at the column base into a number of smaller parts, like submultiples. This operation, in case of hand drawing, could be very difficult, but allows for a very accurate representation. Vignola intermixed both of the processes. Fixing the proportion 4:12:3 between pedestal, column, and trabeation, he dimensioned every single element through the radius division (Migliari 1991) (Figure 3).

The final process, the one used by Chitam, is the most criticized, as it is the least practical. He defines every element separately, eliminating all of the links to the whole construction, thereby going against of all the compositional process of the architectural orders (Migliari 1991). In this project, the models, as the algorithm, have been built following the Vignola process and later, thanks to similitudes, converted to the others version.

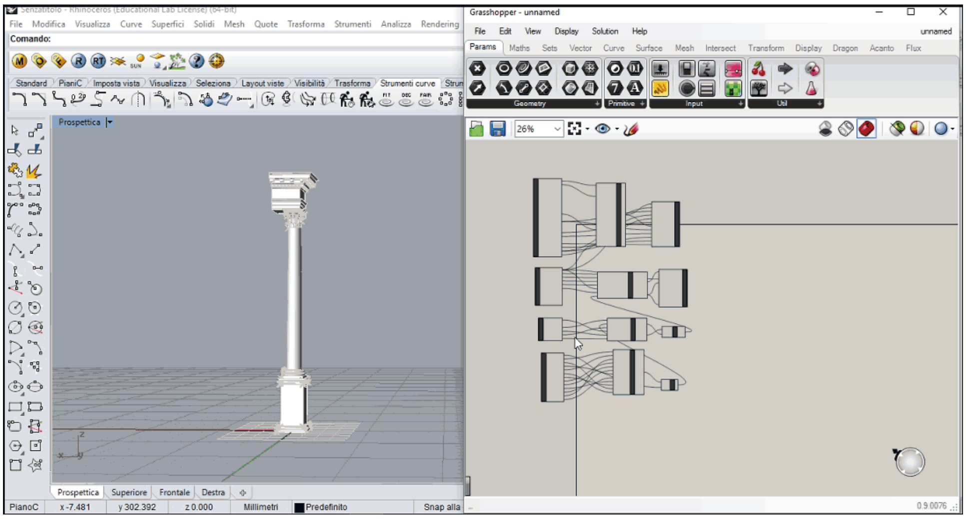

Figure 4. The modelling of a column.

Modeling

Modeling architectural orders begins with generating the smaller parts of these elements, the moldings that are like letters that compose the words that generate the sentences (Morolli 2013). Different combinations of moldings give different parts. The moldings were created by putting the generative algorithms in clusters. This Grasshopper function allows for slimmer, final algorithm-composed clusters that work as independent tools. So, the final algorithm of the entire order can be seen as the positioning of the various clusters of the moldings opportunely scaled. The moldings (analyzed as indicated above) are the torus, the canaliculus, the gulula, and the undula. In the case of the listellum, it has been generated only by a rectangle extrusion. Clusters have been used also for decorative elements with more complicated geometry, like the Corinthian capitol parts. In this case, there are clusters for inferior leaves, the caulucoli, the modiglioni in the Corinthian trabeation, and Ionic dentils. It must be said that some particular geometries – like the Corinthian volute, capitol, and base – were first drawn using Rhino and then via Grasshopper (using an internalized tool) (Figure 4).

This workflow has generated a common skeleton with all the geometries repeated in every element, linked time after time to measures or elements typical of every order. The smaller decorations compose the larger parts of the base, the column, the capital, and the trabeation. Each of these clusters was placed into another cluster.

All the features that diversify the Order versions have been identified and linked to the major clusters. These inputs of various kinds, numeric or geometric, have resulted in new clusters divided by author. The entire system is linked to a numeric tool that determines the diameter dimension of the column base. To compare a model and a real artefact, we input the real diameter dimension using the numeric tool to have a model in the right scale. It is also possible to change the heights of all the elements to the real dimensions in order to have a model that is most similar to the real artefact. If we have a mechanical way to model the Architectural Orders, we can have measurable representations without deep knowledge of modelling and proportional rules (which can serve as an instrument usable by everyone).

The Comparisons

It was possible to create four different models for each Order starting from the same algorithm. These models then generated the comparison pictures to emphasize differences in shape and geometry between each author. For example, the lack of the Vitruvian Composite order is because of the death of the author before of the birth of the Order. This Order - with the Tuscan one before it - is a Roman creation and represented the fusion of the Ionic and the Corinthian Orders. Furthermore, the Vitruvian Orders do not include pedestals in the Greek manner. The same characteristics are also in

Figure 5. The Doric column modelling.

a version by Alberti, who blindly followed the Vitruvian rules.

There are, however, additional differences with respect to Alberti. He does not describe the Tuscan Orders and he has different types of decoration specifically in the Corinthian and Composite capital (De Paoli 2011). The other authors have two kinds of folia. The prima folia is half the height of the secunda folia and both start from the bottom of the cylinder. Alberti draws the secunda folia like the prima folia with the same dimension and puts them over the finish of the prima folia. Alberti, also does not have Culiculum, but only Helices that he calls medium cauliculi. He also uses a different geometry to represent the volute, a theme that would be worth studying further.

After these general considerations were carried out in a dimensional studio, every column was matched with a thickness table to compare the different versions and simplify the drawing.

The Applications

Aiming to show the capabilities of this project, we decided to develop three of the many possible applications:

1. Graphical rendering of an existing historical artefact.

2. Reconstruction of a historical artefact by the only remains.

3. Export of parametric models from Rhinoceros in Revit, and next generate a family of elements.

Graphic Rendering of an Existing Historical Artefact

The first application comes from the survey. Taking

Figure 6. The Ionic column modelling.

a few measurements, you are able to generate an accurate digital model of the reality. In choosing the most similar model to the real case, it is necessary to change some value of the algorithm, like the imoscapo radius (the circumference at the base of the column) and the final height to obtain a full graphics restructuring.

We chose to study the columns of St. Peter's Cortile delle Stelle in Perugia (Figure 5), designed by the architect Galeazzo Alessi (Perugia 1512 - Perugia 1572), a contemporary architect of two of the treaties analysed in this project, Palladio and Vignola. The square courtyard is surrounded by Doric columns, the subject of the first application we developed. The technique of photo-modelling was also used, which allowed us to realize a 3D model in real scale in order to measure the highest parts. Photo modelling is a useful and fast tool, but in this case, it did not produce complete results.

The column is an object of considerable size and full of details. Without more sophisticated instrumentation, it was not possible to obtain an accurate survey in all its parts. A digital representation is possible; however, the image-derived point cloud would require significant postprocessing by a subject-matter expert in order to product accurate measurements. The product of this project aims to provide an instrument that follows the rules of classical architecture so as to skip the reprocessing phase.

Reconstruction of a Historical Artefact of Which There Are Only Remains

The second application was to create a hypothetical reconstruction of a column from its ruins. The starting element is an Ionic capital, from the Museo Civico Archeologico e Pinacoteca Edilberto Rosa of Amelia, of late Republican age, which presents an almost intact echino. The volute, even if damaged, still indicates the form, and it appears to be very close to Vignola's one. The channel of the volutes, below the abacus, is completely absent. This case is not reported by any of the analyzed treatises.

It may be thought that the element indicated, by the museum specification, as abacus may instead be the volute channel. But this is only a hypothesis.

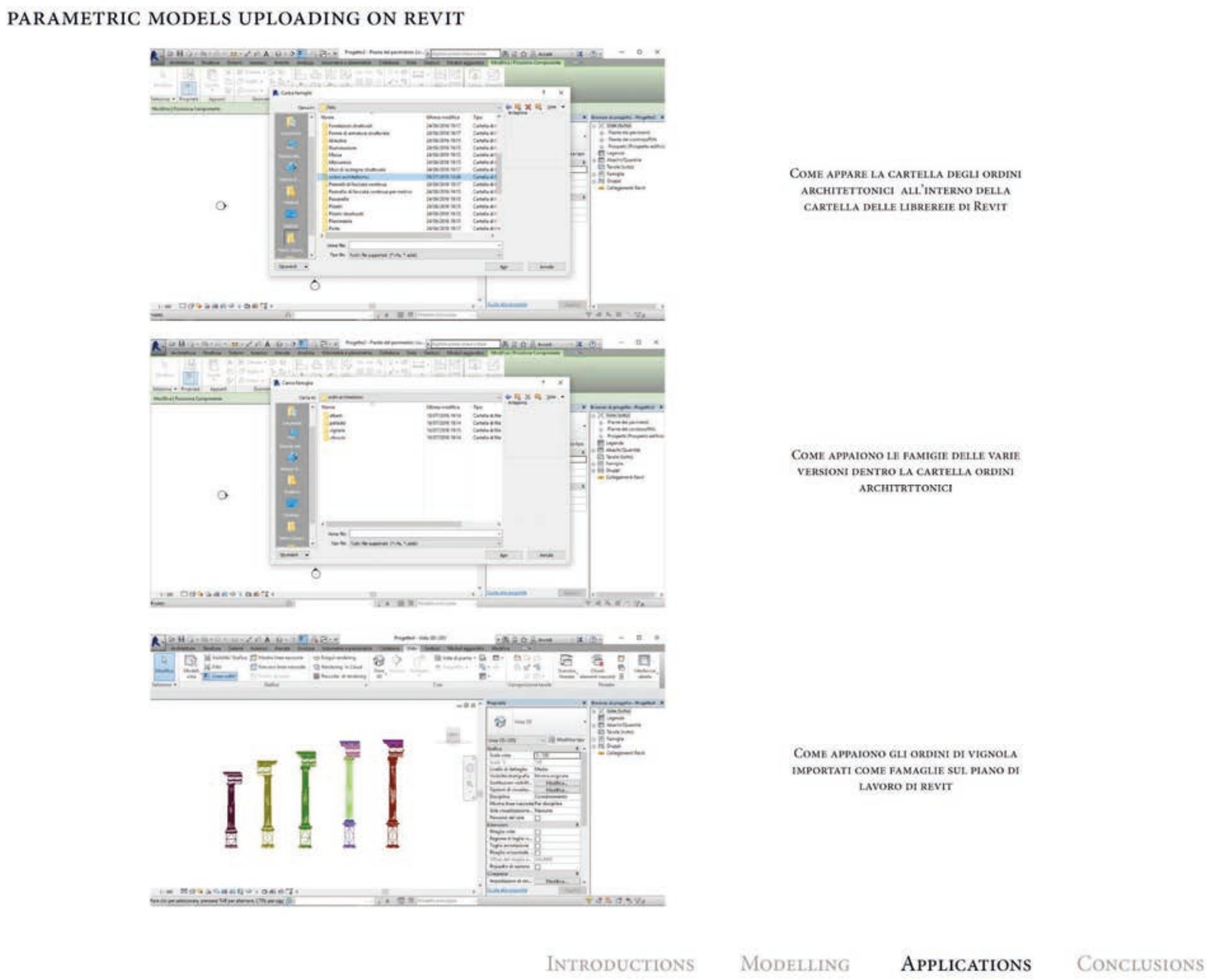

Figure 7. Columns view on Revit.

In the interest of providing more information, both hypotheses have been brought forward.

Moreover, two models were created: one with and one without the channel of the volutes, maintaining the unaltered propositions. Again, we made use of the technique of photo-modeling take measurements without touching the artifact. The 3D model was developed with the Vignola model, applying the appropriate changes in the case of the capital without a channel (Figure 6).

Export of Parametric Models from Rhinoceros in Revit

Revit Architecture is a widely distributed program and, as the central instrument of BIM, its use is growing. The transfer of the model of the Order into Revit has potential important benefits. It enables the parameterization of the models, because the creation of parametric elements in Revit is the center of the system and all its applications. On the other hand, it expands the power of the BIM to the aspects of measurement and to the parametric study of the history of architecture.

Revit is a numerical modeler and it reflects the information as numbers and equations while Rhinoceros is a NURBS modeler and the elements are not always easily transferable. It is necessary to convert the Orders models to polyline to export these in Revit. The new Revit family was imported choosing the character of a Generic Model Metric. This operation was repeated for all the orders and for all the different models of the different treaties, creating a new Directory in the Revit Library containing all the new families (Figure 7). This is demonstrative of how it is possible to create new Revit elements, which are potentially loadable online for widespread distribution. In a hypothetical study and measurement of a historical artifact with Revit, the presence of libraries containing all Orders by the various treaties could be advantageous to study, research, and comparative operations.

Conclusions

This project led to the consultation of multiple sources and the implementation of the rules derived from them. The five algorithms for the representation of Vignola's orders have been defined in the first part of the project, and then these scripts have been modified to determine the algorithms that were adaptable to the different versions. Finally, the algorithms have been discretized and organized with the clusters to simplify the modeling process.

What we have created is a tool to create accurate products from a few key measurements usable also by someone without deep architectural knowledge. In a practical way, the results of the studies of four of the oldest and most important architectural treatises, resolve some problems linked to the difficulty of the representation of the Orders. The proposed models also allow us to make a comparison with actual artefacts and to hypothesize what treaties inspired the author, and to deduce the identity of the architect and the period of construction.

The algorithm actually has broader applications, as the results can also be used in the reconstruction of now lost elements. Additionally, this process could lead to potential developments in archeology. This study could be expanded to the architectural rules of classical buildings, so one can develop, from the remains, a plausible digital representation of the entire construction.

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3D Models and Interactive Communication for Archaeology: The Nymphaeum Ponari in Cassino

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Abstract

This study is part of a broader research project on Roman *Casinum* archaeological heritage and includes tangible and intangible heritage. In the mid-twentieth century, a *nymphaeum* dating from the second half of the first century B.C. was found not far from the core of *Casinum*, an archaeological site, located in the modern town of Cassino in South Latium, Italy. The *nymphaeum* Ponari is part of a Roman villa still completely buried underground. The excavations had been carried out so far have gradually unearthed a well-preserved environment consisting of a rectangular hall with niches topped by a barrel vault. The metric data acquired in a recent digital survey made it possible to develop a virtual model reconstruction of the *nymphaeum* and to design an interactive communication system, on-site and off-site, linked to the nearby museum complex present at the archaeological site. The present article is focused on the documentation, interpretation, valorization and communication of archaeological heritage of the Roman *Casinum* city site.

Keywords: nymphaeum, Casinum, Cassino, Ponari, 3D models, cultural heritage

Appellantur quidem ita erosa saxa in aedificiis, quae musaea vocant, dependetia ad imaginem specus arte reddendam

Introduction

This work is part of a broader research project on Roman *Casinum* archaeological heritage. Even though this archaeological area contains monuments of considerable interest and importance, it has never been archaeologically documented enough to enable the researcher to analyze the individual findings and the environment of the site through a well-structured survey that would allow one to fully explore it. The main finds of the ancient urban layout are the remains of the Via Latina, the amphitheater, the theater and the mausoleum attributed to the Roman matron Quadratilla, part of *gens* Ummidia. There have been some interesting, very recent discoveries related to parts of a Roman *domus* of the imperial period, which should stimulate a deeper, organized study of the town planning system. The part of the *domus*, which was discovered some time ago, is the so-called Ponari *nymphaeum*.

The Environmental Context

Today, Cassino is a modern town lying between Rome and Naples. The city was completely rebuilt after its destruction during World War II and 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 and of the Benedictine monastery of Montecassino are closely linked. The city appears to have been historically consolidat-

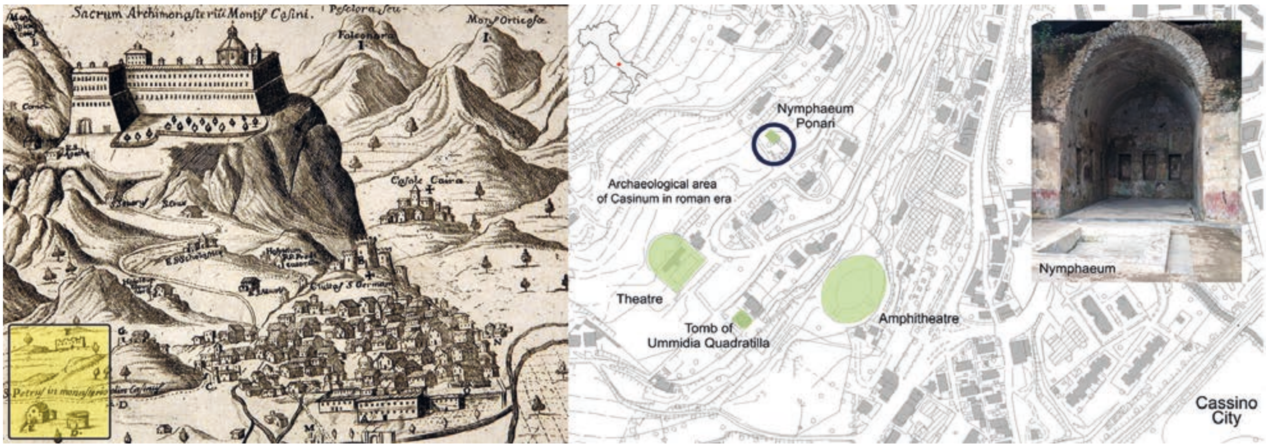

Figure 1. The city of Cassino, the Rocca Janula and the Abbey of Montecassino. On the left, archaeological area with *nymphaeum* Ponari. (Engraving of F. de Grado, in Gattola 1734). On the right: Roman Casinum city, archeological area today.

ed up to the Second World War when any traces of its past were lost. The earliest settlement of the site dates back to the sixth century BC when first the Volsci and then the Samnites permanently settled in the Liri valley, building the first houses of *Casinum* (the name of the ancient city). From a Roman prefecture, *Casinum* became *municipium* and in the third century it was granted the right of citizenship. It flourished reaching the peak of development towards the end of the republic and during the imperial period, and then it gradually sank into insignificance. In AD 529, with the settlement of St. Benedict (founder of Montecassino Abbey and of the 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.

Around the first century BC, after the city of *Casinum* had become a Roman town, there began a process of consolidating 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. The organization of the city was mainly developed on three terraces lying on the hilly topography of the site, of which a large part of the original substructures still exists, expanding the city to the east, outside the city walls, down the steepest area. The settlements already existing during the Augustan period and the late imperial period when the city (at the end of the first century AD) reached an area of about 10 hectares, led scholars to hypothesize an urban network was structured in the shape of a square of two *actus*.

The monumental structures of the present archaeological area are (Ghini and Valenti 1995): the theater; the core of the Augustan town plan, brought to light in 1935-36; the amphitheater dating back to the second half of the first century AD, which has an elliptical shape of modest dimensions; the so-called tomb of Ummidia (1st century BC - 1st century AD), a building planned on a Greek cross, with the central part covered by a hemispherical dome intersected by four arms; and the *nymphaeum* called Ponari, which was built on a rectangular plan with a barrel-shaped roof, closed at three sides and fully open at the front (Figure 1). The building is connected to a well-structured floorplan of a rich *domus* (Polito 2013) with valuable floor mosaics, as well as fragments of walls of the rooms, preserved at the height of more than 2 m, whose wall decorations are articulated in architectural schemes with small paintings of mythological-symbolic subjects or idyllic-naturalistic themes.

The *Nymphaeum* Ponari

The word *nymphaeum* has a double meaning: the first is of Greek origin and refers to a place (often caves) consecrated to the nymph goddess; the other one is of Latin origin and refers to a place with water and fountains. In the course of centuries, the architectonic sense of *nymphaeums* in relation to the position and their typology has changed significantly. By and large, the architectural evolution of the *nymphaeums* in relation to their position can be the following: public *nymphaeums* (monumental intentions - II-IV century AD), located along the main roads or at crossroads; composite *nymphaeums*: interiors for public buildings; private *nymphaeums*, for rich

Figure 2. Similar *Nymphaeums* in Italy: a. *nymphaeum "Q. Mutius"* in Segni (Rm); b. *nymphaeum "Dorico"* in Castelgandolfo near Lake Albano (Rm); c. *nymphaeum "Egeria"* in the park of Caffarella (Rm); d. *nymphaeum triclinium* in a Roman villa in Minori (Sa).

domus decoration. The main typological models of the Roman nymphaeums are: environments in natural caves; environments in artificial caves; environments in rooms without niches but with functioning, real monumentalized fountains, sometimes with a bottom apse; environments in rooms with niches in the walls; the basilica plan environments; and other forms.

Another renowned typological classification, proposed by Mingazzini (1955, 1957), distinguishes these buildings according to their location and size. The subdivision is essentially split into three categories: *nymphaeum* for buildings related to monumental public fountains; *musaeum* for structures with natural grottoes, even if artificially modified; specus estivus for all artifacts with specially designed fountains. The latter can be divided into three sub-categories: semi-underground, i.e. partially constructed in the ground; completely constructed above ground; or conceived as an integral part of a villa, or a building (Neuerburg 1965: 27-29). A further category for the typology related to villas is found in sub-types linked to the layout and architectural type. Among these, a particular typological category referring to nymphs, is the so-called "chamber". Chambers appeared at the end of the III century BC and took on more varied and articulated forms over time. The "chamber" essentially has a rectangular layout, in most cases enriched by niches in the walls, with a recess or an apse in the bottom wall, while open at the front and generally with a barrel -vaulted roof. Initially, the "chamber" building constituted a direct development of the 'natural grotto' model, which is connected to the recurrent use of rustic symbolism. Because of its location, the *nymphaeum* Ponari recalls *Specus estivus* as described by Mingazzini (1955, 1957) and, owing to its geometric and typological characteristics, can be considered to belong to the 'chamber' variety.

In Italy, there are some examples of *nymphaeums* similar to that of Cassino in shape and state of conservation (Figure 2): *nymphaeum "Q. Mutius"* in Segni (Rm); nymphaeum "Dorico" in Castelgandolfo near Lake Albano (Rm); *nymphaeum "Egeria"* in the park of Caffarella (Rm); *nymphaeum triclinium* in a Roman villa in Minori (Sa).

The "*nymphaeum* Ponari," identified in the 1940s, thanks to the investigations carried out by the archaeologist Gianfilippo Carettoni (1912-1990) (1940), was the subject of a subsequent intervention by Massimiliano Valenti (1992) in the 1990s, especially in 1998, removing the land fallen meanwhile due to the steep slope of the ground on which it stands. More recently, in 2009 and 2014, the monument was the subject of work that ensured its preservation (Figure

Figure3. The *nymphaeum* Ponari in the archaeological site of *Casinum*.

3). Thanks to some further discoveries made during this work, architect Silvano Tanzilli (2016), then director of the archaeological site at Casinum, elaborated a reconstruction of an alleged *domus*. To date, however, the elements to support a plausible interpretation of the presence of a *domus* are still insufficient.

With the first regeneration of the *nymphaeum* there also emerged the rich decorative elements that distinguish it: a floor mosaic represented by a three-color tessellated floor with *crustae* in marble, and a "rustic mosaic" on the wall that was subsequently overlaid with a plaster of pictorial decoration imitating marble slabs, defined by a reproducing range of painted, colored shelves in perspective (Betori, Valenti & Tanzilli 2009).

As already mentioned, the decorative wall and flooring system are immensely rich and interesting. In particular, the wall decoration consists of two decorative systems, the second of which was added at a later date. The oldest one, dating to the Late Republican - Early Augustan period is visible only in some areas where the next one collapsed (right wall). It is characterized by a rustic mosaic with Egyptian blue rhomboids, fragments of limestone and polychrome glass as well as various kinds of shells. Even though it is significantly damaged, the decoration allows for the tripartite decorative pattern used to be identified. The pattern consists of a structured top section with parallel strips, a middle part with a vertical scan, featuring three niches on each wall, topped by a triangular crossbar, and the lower part defined by a horizontal strip enclosed between two rows of Egyptian blue mosaic tiles with alternating circular and rhomboidal motifs originally coated with glass tiles. The bottom part encloses a diamond shaped lattice, the result of the alternation of double diagonal rows of "tellins". As for the later wall decoration, the rustic mosaic from the imperial age overlays a plaster painted with fresco paintings with geometric decoration on false marble slabs (imitation of caristio and numidian marble slabs), retaining the previous horizontal tripartition of the wall. On the bottom wall the strip below the niches consists of a pseudo-perspective representation of red, white and blue protruding shelves (Figure 4). Lastly, the floor decoration has a polychrome checkerboard mosaic of small horizontal textured weave tiles with insertion of irregularly positioned marble chips, with a double strip of black tile frame along the long, white walls on the bottom one. A marble trunking (*bardiglio*) further defines the latter wall, probably used to collect water filtering down from above.

Lastly, the typological and geometric characteristics of the structure and - in particular - the decorative elements, have allowed the *nymphaeum* to be placed in a specific chronological range. Indeed the mosaic floor recalls decorative styles commonly used throughout Lazio and the rest of Italy between the end of second century BC and the end of the first century BC, with Pompeian examples created until the first century AD. The original layout can be dated to the late-republican age, between the end of second century BC and mid-first century AD, on the example of some similar mosaic creations from that era (e.g., villa of Barcola near Trieste). Even the shell-like

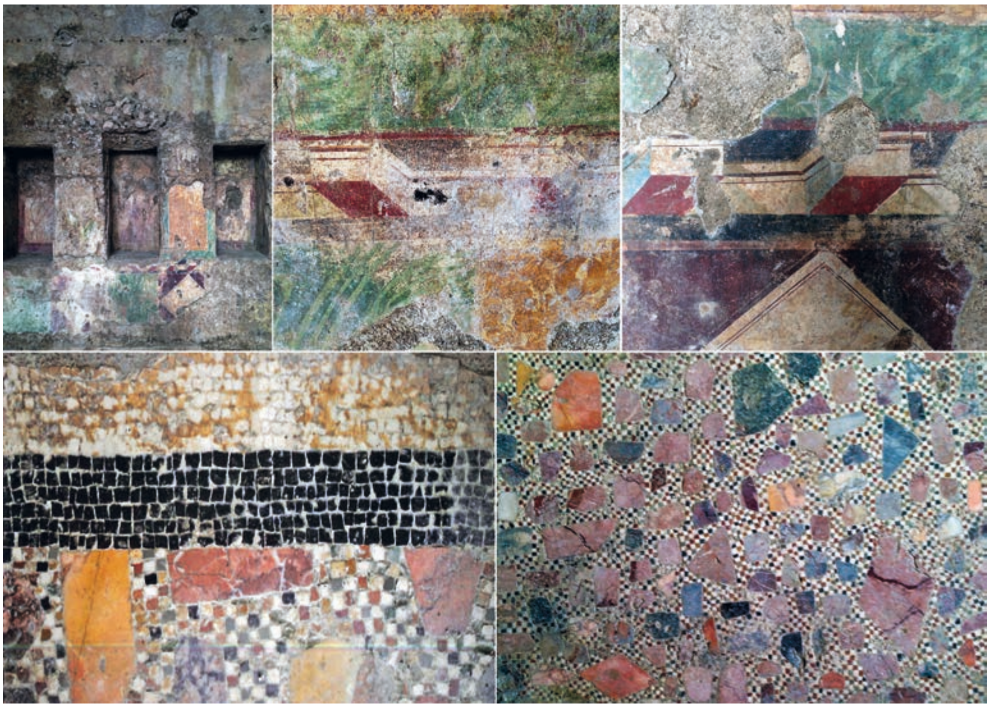

Figure 4. The rich decorative apparatus, wall and floor details: below the niches, is a pseudo-perspective representation of the architectural elements, colored red, white and blue; while the flooring mosaic system is formed by a three-colored tessellated floor with *crustae* marble, and a "rustic mosaic".

mosaic wall became popular around the middle of the first century BC, with numerous references even in central-southern Lazio. The most outstanding is the *nymphaeum* Segni, Frosinone province, the date of which can be established by the architect's signature *Q. Mutius*, found on the structure and his association with the family of *Mucii Scaevola*. Moreover, the subsequent decoration can be traced back to the imperial era.

The Integrated Digital Survey

An innovative contribution of this research regarded new activities at the archaeological site based on an integrated digital survey. In recent years digital technology has produced a convergence and integration of different instrumental survey methodologies. Some of them are already known, such as topographic mapping (merged into the wider scientific area known as geomatics), while others are more innovative, such as laser scanning and photogrammetry. In the field of 3D shape acquisition, the integrated digital survey configures as the interaction and integration of three distinct methodologies: topographic, laser scanning, and 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 data acquisition, processing, and management (Adembri et al. 2016).

The experience in progress at Cassino is significant for the particularities of the site, highly integrated with the existing urban fabric and with a topography that makes the stratigraphic study of the different archaeological phases more difficult. Visible today is only part of the Roman *castrum* and some areas, such as that of the *nymphaeum* Ponari, appear as isolated incidents, while it is generally agreed upon that these should be seen and relocated within a unitary urban configuration. Within this site there are archaeological remains of different type, size, condition and construction features. Therefore, it's important to adopt the best strategies for acquiring and processing data, related to the specificity of individual archaeological features. The starting 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 reflectance value when using the laser or the RGB color value with photogrammetry).

On *nymphaeum* 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 from the internal camera on the 3D scanner with a higher resolution

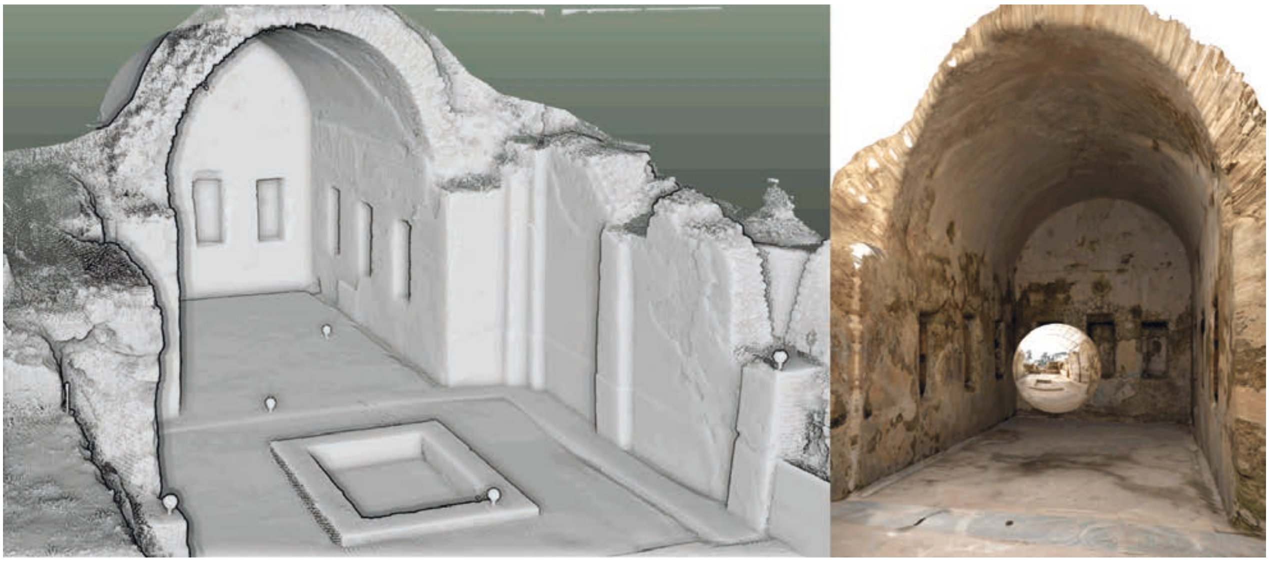

Figure 5. 3D elaborations from point cloud with and without texture. The texture of the 3D model was created and mapped using HDR spherical panoramas.

one in the 3D model. The photos made with the external camera have enabled us to use the High Dynamic Range (HDR) technique to achieve the best exposure compensation. On the walls of the *nymphaeum* there are many traces, also small ones, of the different stratigraphy. These traces can help the archaeologists to understand the several coatings that have been applied over time. A careful study of these traces is possible only through a right integration between the metric data of the point cloud and the high-resolution photos. The survey of the *nymphaeum* Ponari also takes account of the current excavations that brought to light the remains of walls with well-preserved frescoes of a high aesthetic quality.

The first step of the post-processing phase is the elaboration of the point cloud from the laser scanner, obtaining first a 3D model reconstruction as a polygonal mesh surface. The quality of the model depends on two factors: the quality of the point cloud and the Poisson surface reconstruction algorithm (Kazhdan and Hope 2013), used for generating the mesh surface from the point sets (Figure 5). In this way, it's possible to switch from a discrete model for points to a discrete model for surfaces. The photos made with the internal camera of the scanner can be replaced with other photos made with an external camera which improves the pixel resolution and the exposure applying the HDR technique or the standard Low Dynamic Range (LDR) mode.

This textured 3D model can be used in the initial investigations on the shape and geometry, extracting specific information, such as horizontal or vertical slices used for 2D graphic elaborations. Through the plan (Figure 6) and the section (Figure 7) it is possible to see the entire area already excavated and even that small part of the *domus* only partially excavated. The *nymphaeum* is composed of three parts: the rectangular hall with niches, covered by a barrel vault of about 7.50 m long and 4.60 m wide; an open area with a tub at the center which is about 7.50 m long and 6.30 m wide; a filter area linked with the *domus*, perhaps covered, about 3.60 m in width. The measurements are in meters and no metrological analysis has been carried out to obtain the correspondence with the Roman foot because measurements often vary considerably, so it is difficult to identify exactly the measure of reference.

The covered hall contains three niches for each of the three walls. There were certainly some decorative elements (moldings and cornices) that can be partially reconstructed on the basis of the traces still visible in the plaster. There was also a very rich pictorial decorative element that can be largely reconstructed in its original configuration thanks to the many painted parts still in good condition. The layering of plaster allows us to clearly distinguish the different coating techniques corresponding to the different historical phases. Behind the latest layer of plaster, probably dating back to the second century AD, there are traces of a rustic mosaic covering made of stones and shells on the NE wall. Observing the plan (see Figure 6), the overlapping of three different

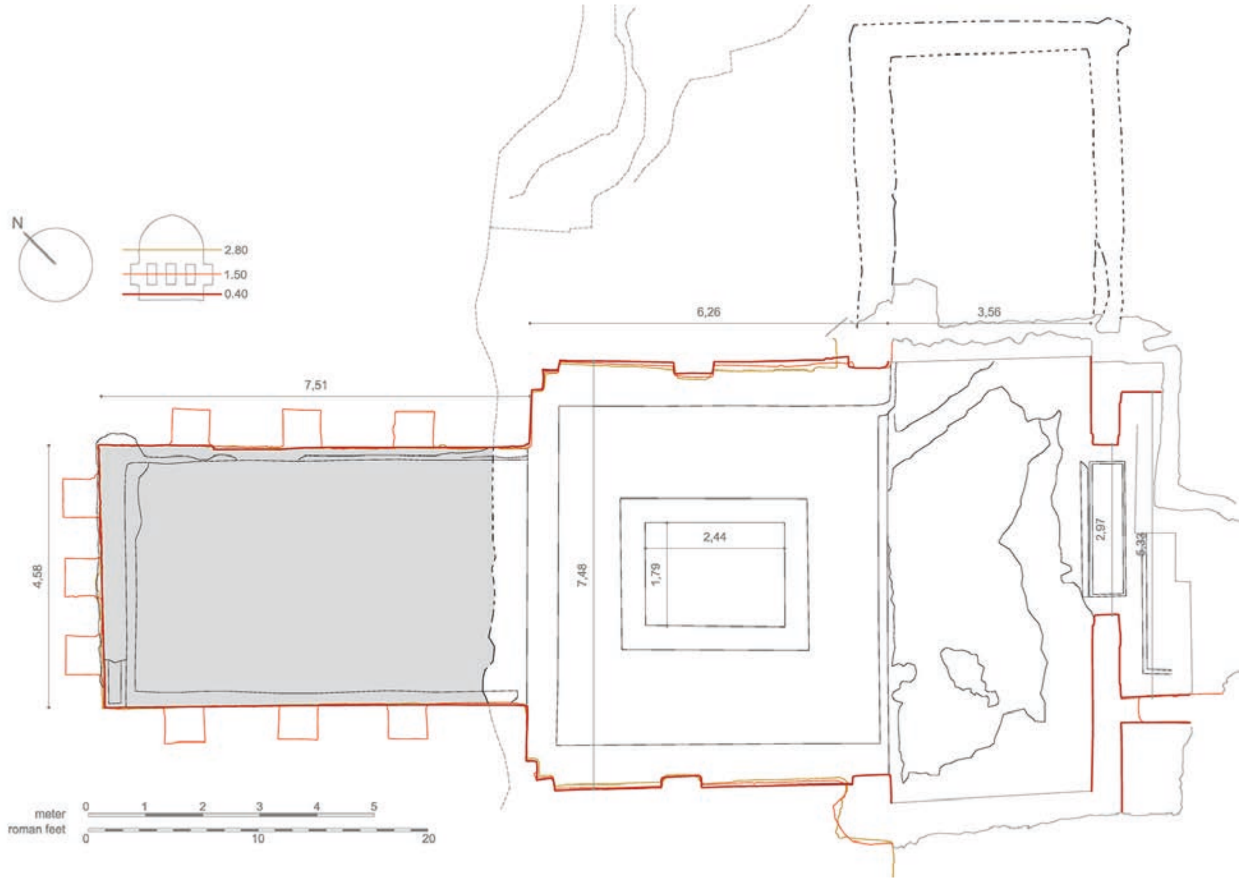

Figure 6. Plan of the *nymphaeum* Ponari. The plan includes three different horizontal sections to highlight the several misalignments, horizontal and vertical.

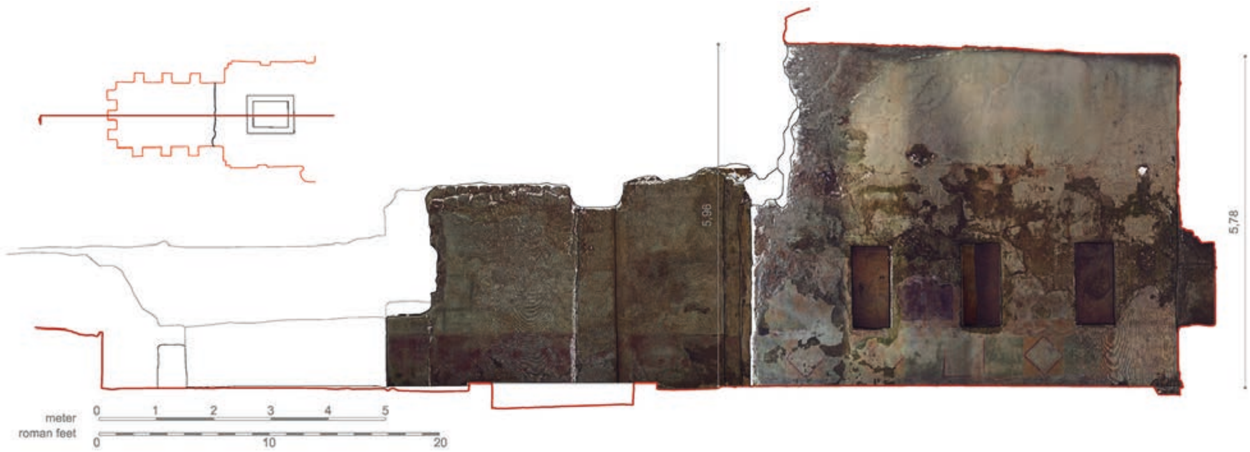

Figure 7. Longitudinal section with the front textured using the spherical panoramas.

horizontal sections made at three different reference points allows us to evaluate the differences from the possible original wall alignments that have undergone noticeable deformations over time.

Some elaborations of the plan and the section allow us to highlight some particular features of the *nymphaeum*. In Figure 8 note, for example, the different axis of symmetry between the *nymphaeum* and the part of the *domus* that is still visible. The niches have the same size in height and width, but there is no symmetry on the two long walls. Even in the open space where there is the water tub there are two unaligned pilasters. These differences can be ascribed to different construction periods. The over-

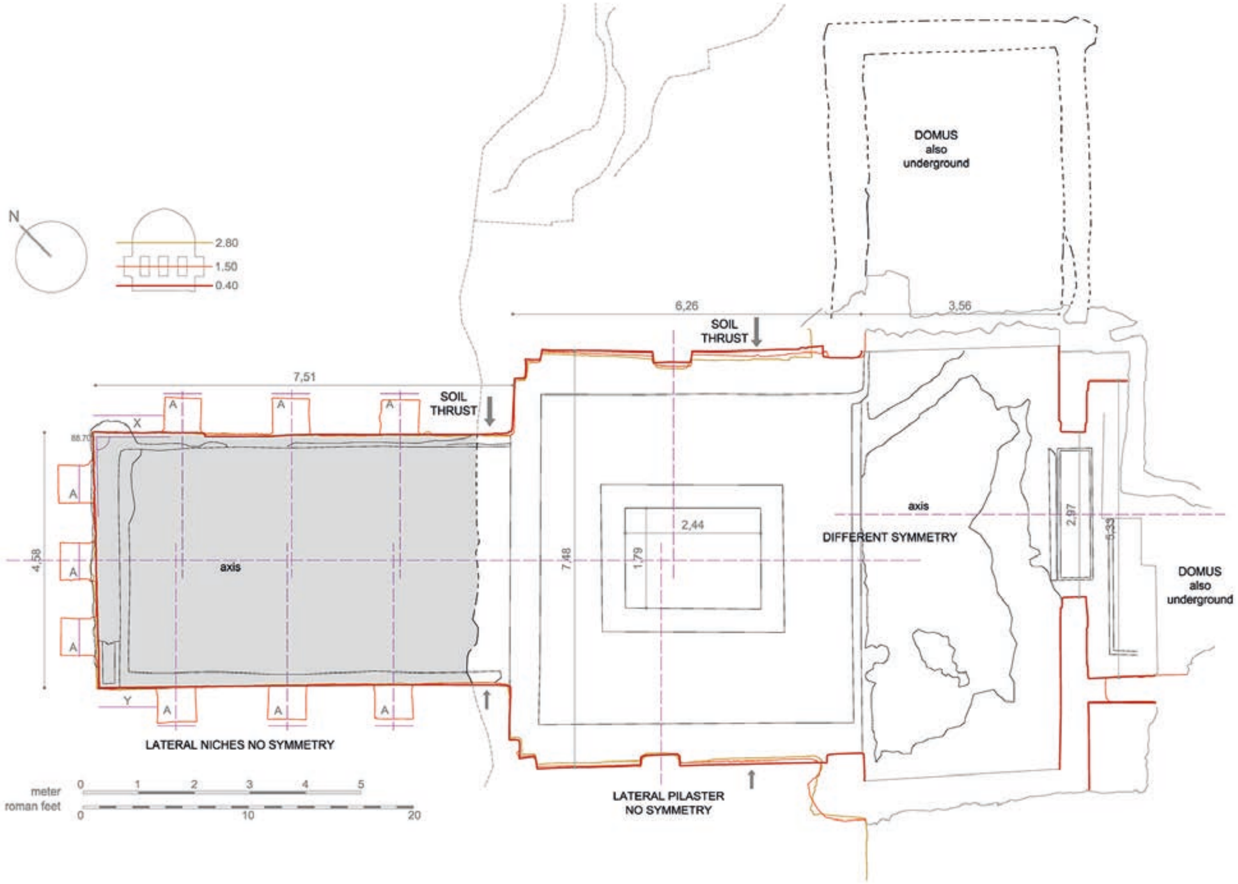

Figure 8. Plan in which some particular features of the *nymphaeum* are highlighted.

lap of the horizontal sections allows us to evaluate the deformation undergone by the whole structure. Deformations are largely attributable to the lateral thrust of the ground.

Other elaborations made directly from the point cloud (such as the elevation maps) allow us to highlight some details not visible to the naked eye. In this way, it's possible to figure out the difference in altitude of the various parts that compose the floor. In the back wall of the *nymphaeum* there is a canal through which the water flows (still partially visible). It is important to note also that the floor of the covered chamber has not undergone particular sagging and is still perfectly level. Figure 9 allows us to verify two things: the correspondence with the round arch geometry of the barrel vault and the deflection upwards of the outermost part of the surface in consequence of the lateral thrust of the two load-bearing walls.

Particularly interesting is the study of the parts of plaster on which it is still possible to observe decorative geometric motifs. As mentioned, the peculiarity of this *nymphaeum* is that an older layer of finishing clearly emerges from under the layer of frescoed plaster (with geometric figures of different colors, a pseudo-perspective frame and panels with drawings depicting different types of marble). The application of different visualization filters on the pattern derived from the point cloud (i.e., "ambient occlusion"), allows us to analyze in detail the imprints on the plaster of the various mosaic tiles. Among these are also some imprints of shells and other natural elements that were used in the decoration according to a well-defined geometric design (which was only partially resumed in the later layer).

Interactive Communication

Another research activity of the project included an on-site application using innovative ways of cultural heritage communication. Recently a museum (named "Museum Carettoni" in honor of the archaeologist who worked on this site for years) has been opened inside the archaeological area. Given that currently the *nymphaeum* is outside the traditional

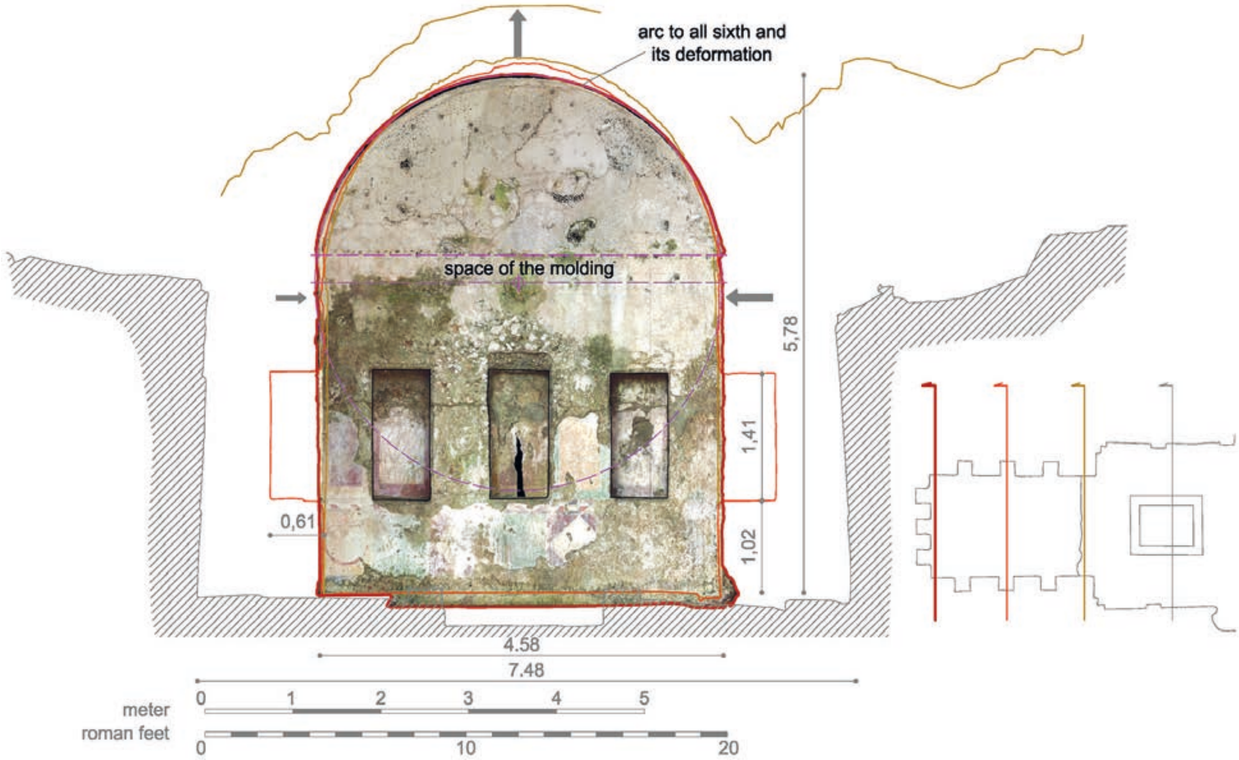

Figure 9. Transversal section in which some particular features of the *nymphaeum* are highlighted.

visitation circuit because it is still a building site, the processing of the models shown here represents a real opportunity to set up in the museum an interactive box for multimedia virtual tours using immersive virtual reality. Today, the ways on cultural heritage communication can be very diverse thanks to the great diffusion and versatility of digital technologies. However, each context evinces its specificities over which some applications may have greater or lesser communicative effectiveness (Frassine et al. 2014).

The virtual tours, for example, can be used on fixed or mobile devices (smartphones or tablets). In the first case, there is almost always an off-site communication mode that is far from the object or site we are visiting; in the second case it is also possible to activate on-site procedures, in direct contact with the cultural heritage. In this case, the effectiveness of communication is certainly greater as it eliminates the loss of visual quality due to technical limitations of mobile devices, which can lead to the loss of the user's attention. In the case of *nymphaeum* Ponari, a very important aspect to consider is the level of freedom of movement within the virtual space. In the virtual tours based on spherical panoramic photos, space exploration is linked to a predefined points-of-view, while in 3D-based virtual tours, it's possible to interact more freely with the virtual model obtaining a greater communicative impact. However, the quality of the experience depends largely on the level of model accuracy, sensory immersion (obtainable with devices that are still too sophisticated and expensive for mass use), as well as the functionality and simplicity of the navigation tools.

The project that has been developed for *nymphaeum* Ponari involves the installation of a multimedia station within the Carettoni Museum (Figure 10). The communication interface is based on a virtual tour consisting of four spherical views that allow us to navigate within the remains of the *nymphaeum* by rotating the 360° view with simple and intuitive interaction modes. It is also possible to take advantage of greater spatial immersion using virtual reality optical devices. Spherical views have a number of links (hotspots) through which activate more in-depth knowledge pathways (details, historical documentation, comparison with other *nymphaeum*, etc.), thus diversifying communication in relation to the user. Particular care is given to the integration of the visual component with that of the storytelling voice, rather than written texts. This is because in this kind

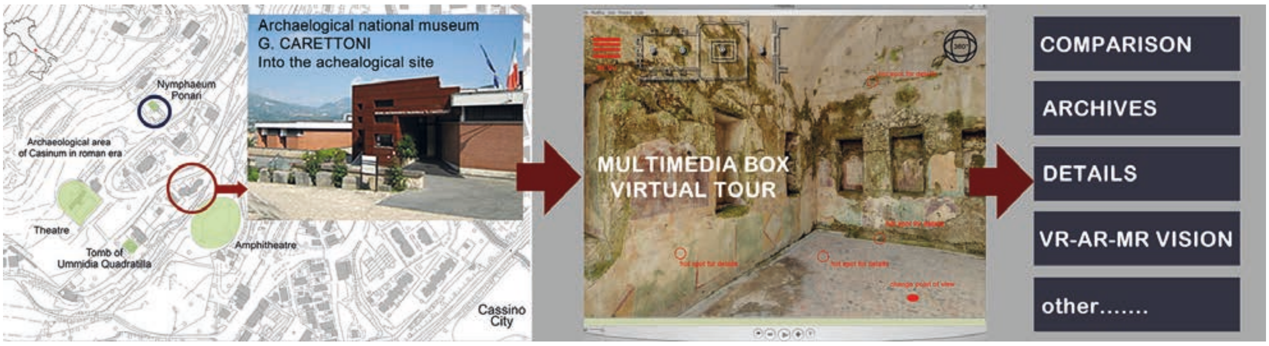

Figure 10. Project of multimedia box to be installed inside the Archaeological National museum "G. Carettoni" built into the archaeological site of *Casinum*.

of communicative experiences the voice message is much more effective than the written message.

This aspect of the project, which is still under development, represents a concrete opportunity for visitors of the archaeological area to know a currently inaccessible place, which is particularly interesting not only for the state of conservation of the spatial context but also for the refinement of some decorative details, largely well preserved in their original features.

Conclusions

This study is part of a broader research on *Roman Casinum* archaeological heritage and includes tangible and intangible aspects of that heritage. Digital technology can be an important means for optimizing resources for the conservation and enhancement of the cultural heritage so widespread in our territory. After an initial period of experimentation, today a practice that is common among superintendents, surveyors, archaeologists and scholars has established itself. The use of digital survey and 3D modeling for the documentation and study of archaeological sites and historic buildings, has increased significantly in recent years. The survey allowed us to elaborate 2D and 3D representations useful for expanding our knowledge of the nymphaeum Ponari. The study is also an important step to program the future excavations of the Roman domus. Moreover, the 3D models can be used for a new form of communicating cultural heritage both inside the nearby archaeological museum as well as in off-site places.

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Digital Documentation of Masada Fortress in Israel: Integrated Methodologies of Survey and Representation

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Abstract

The general aim of the MRP - Masada Research Project is to create a comprehensive digital documentation of the archaeological site of Masada. Integrated 3D digital survey methodologies allowed the acquisition of all the information necessary for the creation of a digital database. This paper describes some results about the interaction between complex sets of data, acquired with various tools, and its dissemination through contemporary representation systems. The research conducted explains how the "migration" of reality in a virtual environment depends strongly on the structure of an efficient workflow and the proper use of available technologies. Digital tools allow the creation of customized and open-ended knowledge systems through which users can interface with the elements of the space around them interactively and be/become more conscious about the archaeological heritage.

Keywords: virtual heritage, digital survey, 3D laser scanning, structure from motion, Masada

Introduction

This research project is about the digital documentation of the Masada archeological site, which was conducted in accordance with the heritage sites management rules of UNESCO and with the agreement of Israel Nature and Parks Authority (NPA). The research took place during four years of international missions in which professors and researchers from the Italian Universities of Florence and Pavia participated, in collaboration with the Schenkar college of Ramat Gan (Tel Aviv), and the results were made available to the NPA in the form of a digital document to support the development of the site's "management plan." The work represents the first complete digital documentation of the current state of the site and demonstrates the possibility of using advanced digital technologies in conditions of extreme environmental difficulty, as the orographic and morphological nature of the site present terrain unevenness of over 300 m and inaccessible mountains sides. Thus, the use of Laser Scanners with 300 m range and SfM terrestrial photogrammetry methods have permitted the realization of the photogrammetric survey of the inaccessible slopes (obviously with less detail than the plateau of the site). Today there are no complete 2d drawings of the entire site of Masada, but only some planimetries realized through topographic survey, and therefore not detailed.

Each participating University developed research guidelines, specifically, the University of Florence team created interactive multimedia resoureces to help promote tourism at the archaeological park. The highly reliable 3D digital models made by the working group also serve to virtually preserve the site, which is in clear and indisputable danger from environmental and anthropogenic factors. Finally, the paper outlines case studies that show the possibility and/or opportunity of specific in-depth analyses regarding the architectural structures of the site and decorative details, such as the floor mosaics.

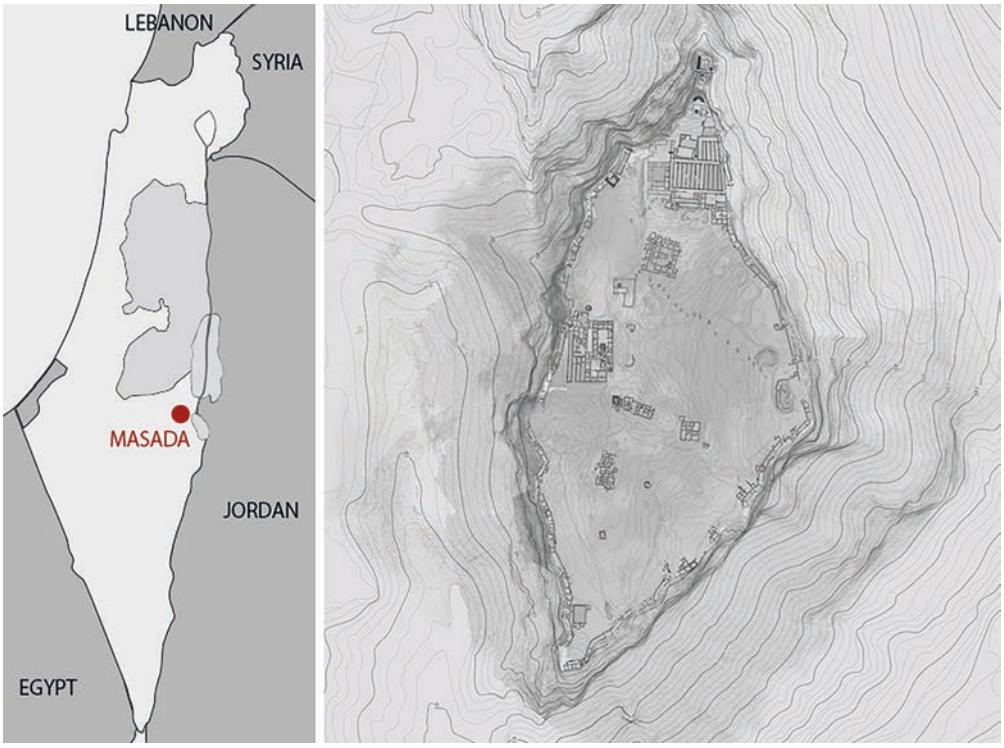

Figure 1. Location map of Masada and general plan.

Background: Virtual Reality and Visualization Tools

The documentary corpus acquired during a survey campaign is crucial for the knowledge and understanding of a site. In the archaeological field, traditional 2D documentation is useful for recording excavation documentation, status of sites, and activities. 2D plans are supplemented by 2D drawings of elevations for the documentation of masonry technologies, architectural types, and stratigraphic analysis.

3D models, on the other hand, are more suitable tools for remotely assessing the preservation conditions of the site, understanding architectural typologies, virtual tours, and virtual reconstructions. The construction of 3D models offers the opportunity to generate highly immersive "virtual words" where it is possible to reach a high level of realism. The experience of navigating and discovering virtual worlds is now available to everyone, and it is also possible to easily build virtual scenarios and interactive 3D models. VR (Virtual Reality) and AR (Augmented Reality) applications allow the creation of interaction and visualization systems that enable active and constructive participation by the end user. These dynamic worlds, easy to use and content-rich, are able to arouse emotions in those who use them and encourage them to increase their use. Virtual worlds have been created because people have exhausted geographic space. The virtual worlds are complementary, and do not serve as substitutes for the real world (Dodge and Kitchin 2001; see also Gerosa 2008).

For every different research field, diversified methodologies must be adopted, in fact "a computer-based visualization method should normally be used only when it is the most appropriate available method for that purpose," and "it should not be assumed that computer-based visualization is the most appropriate means of addressing all cultural heritage research or communication aims" (London Charter 2009:2.1; see also Brusaporci 2016). The 3D models that make up these "new worlds" often reach such complexity that they might fail to guarantee the quality of the interactions that the user would like, such as the rendering quality or the fluidity of the visualization. It is therefore necessary to carefully study the possible end-user applications in order to build low-poly 3D models (Guidi and Angheleddu 2016).[1]

1 "The article explains a re-coding method based on displaced subdivision surfaces that makes it possible to adapt the re-coded 3D representation to the metrological limitations of the 3D capturing technique used for generating the original mesh. The resulting re-coded model can be therefore considered as close to the physical object/scenario, as the original acquired mesh, with a

Figure 2. View of Masada plateau on the side of the Roman Ramp.

In this sense, we find the concept of multi-scaling 3D models useful. This is the ability to create 3D models at different scales, where general 3D models can contain detailed 3D models rich in specific and more detailed content. Thanks to AR applications, it is possible to overlay infinite layers of enriched content, continuously upgradable and implementable (Parrinello, Picchio & Bercigli 2016).

The Archaeological Site of Masada

The site of Masada, discovered in 1828 by Edward Robinson and Eli Smith, stands on a mountain that rises east of the Dead Sea in southeastern Judea, and is nowadays one of the most important archaeological UNESCO sites in Israel. The historian and archaeologist Adolf Schulten studied the Roman siege camps around the site in 1933, but the top of the fortress was dug only during the excavation activities that were carried out between 1963 and 1965 by the expedition under the supervision of the archaeologist Yigael Yadin (1968)[2]. In 1966, Masada and its territory become a protected area by the NPA and it was opened to the public. It became a UNESCO protected site in 2001, and today the complex is open to tourists and includes a Visitors' Centre, a cableway for the faster connection between the Centre and the main site area of the fortress on the plateau atop the mountain (Figure 1).

An important aspect of the actual management plan of the site is the decision to proceed without further research excavations on the main site "in the period of the current generation," limiting this type of activity only to the finalization of projects for preservation, maintenance, or restoration. According to the WHC Nomination Documentation (2001):

> [t]his is a site that remained untouched for more than thirteen centuries. The buildings and other evidence of human settlement gradually collapsed and were covered over until they were revealed in the 1960s. There have been no additions or reconstruction, beyond an acceptable level of anastylosis, and inappropriate materials used in early conservation projects are being replaced. Limited restoration works have been carried out to aid visitor interpretation with original archaeological levels being clearly defined by a prominent

great advantage in terms of 3D representation size, UV parametrization, topological coherence, and scalability".

2 The work concerning the stratigraphy and architecture of the buildings of the site, began in 1989, after the death of Yadin in 1984, and was finally published in 1991. The author was Ehud Netzer, who participated in the expedition and, at the end of the excavation campaigns, he was the architect responsible for the preservation and restoration of the site before it was opened to the public in 1966 (Netzer 1991).

Figure 3. Example of division of the Western Palace rooms and denomination with unique identification codes.

> black line set in the new mortar joints. Certain significant archaeological elements, such as the Roman camps and siegeworks, remain virtually untouched. The authenticity is therefore of a very high level.

The archaeological site of Masada is built on a rocky plateau standing between the elevations of 35 m and 60 m above sea level (about 450 m above the Dead Sea). The plateau is about 650 m long and 300 m wide overlooking the depression of the Dead Sea, and the morphology of the mountain gives it the appearance of a natural fortress (Figure 2). The most important phase of evolution of the site, from the perspective of quality and quantity of structures, dates to the reign of King Herod who oversaw the construction of a complex of well-structured and designed. Construction took place in several stages throughout his reign. Subsequently, with the outbreak of the Jewish revolt against the Romans in 66 CE, one thousand zealots conquered the fortress of Masada, and the great palaces of Herod suffered several changes. New rooms were created in the existing ones, in order to adapt them to everyday life. A few years later, after the destruction of the Temple of Jerusalem by Titus, Masada was the last bastion of resistance against the Romans until the siege that saw the construction of the Roman ramp and the defeat of the zealots (73 CE). For a long period, the site was uninhabited. Later, during the Byzantine period, a small monastic community settled on the plateau and built a church. There is no further documented information about the presence of other occupants and even for this the site was discovered only in the nineteenth century.

The Complexity of the Site and the Management of the Survey

The general aim of the Masada Research Project is to create the comprehensive digital documentation of the archaeological site. The site is subjected to various types of risks:

- Seismic risk (the site sits close to the Great Rift fault line).

- Hydraulic risk (the soil is very dry and occasional storms can create strong runoff events)

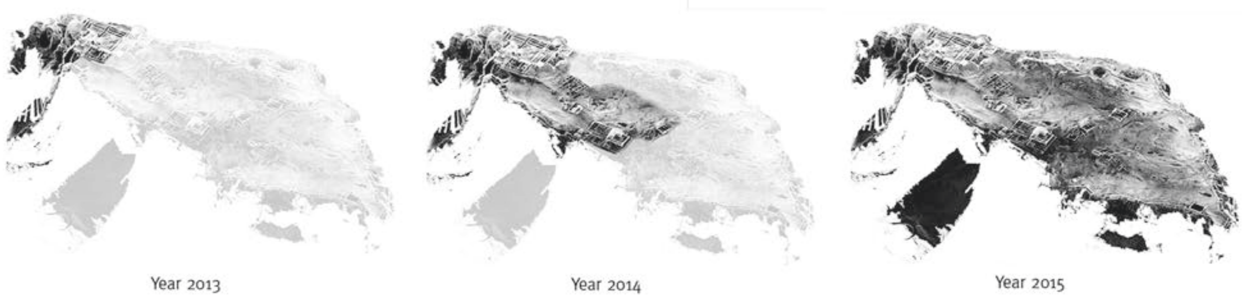

Figure 4. Progress of the digital database (point cloud) during the years of Research.

- Tourist pressure (the site endures 1.25 million visitors per year, mostly during the summer).

- Sun exposure (most of the site is exposed to direct sunlight and high temperatures).

- War / terrorism (the unstable political situation in the Middle East exposes the site to the threat of terrorist or war damage).

The Masada Research Project includes a series of survey campaigns organized over four years[3]. Data acquisition was accomplished by laser scanning and photogrammetry. The point cloud obtained by the laser scanner forms the raw data of the documentation database together with all the photos acquired. Furthermore, the team has processed the point cloud in order to extract data useful for 2D drawings (plans, sections, and elevations), 3D models, and multimedia content. 3D models can represent the site "as-is" but can also serve as the basis for a digital reconstruction that will be able to illustrate the state of knowledge about the site and the various transformations it underwent during the course of history. Among the aims of this project is the development of opportunities for cultural partnerships between Italian and Israeli academic institutions.

The technological progress in the field of archaeological survey, where the use of digital techniques is now strengthened (from the organization and acquisition of data to post-production), has a series of consequences, the most significant of which appear to be the increase in the amount of data and of acquired information. This consequence translates into the ability to develop new documentation and dissemination methodologies in order to obtain the best results from the digital potential. For system consistency, but also for convenience in terms of space and time costs, all these results must be organized in a tidy system, which needs to comply with the digital tools. The database, the website, and the interactive map are intended to be concrete examples of the ability to structure the complex data collected, to organize open systems for conserving and disclosing information, and above all, to contribute to the preservation of an archaeological site that is truly a part of the human heritage.

Integrated Methodologies of Survey

In order to build a complete digital documentation of the Masada site, many data were acquired during the various survey campaigns. The first necessary step was the planning of operations and the construction of a project timeline. Masada is built on a plateau that does not allow easy access to all areas. It is also composed of morphologically complex rooms, particularly in the northern area of the terraced palace. Simultaneously with the planning of the survey phases, a data archive was built for the purpose of organizing past records according to a system of codes referring to the publication of E. Netzer (Netzer 1991:xvii-xxviii) and in order to preserve the original data acquired so that could be orderly and easily accessible in the future. Each of the rooms in the site corresponds to an easily identifiable code on the 70s baseline map and later up-

3 In 2013, 2014 and 2015 campaigns ware directed by a team of professors from Italy, S. Bertocci (University of Florence) and S. Parrinello (University of Pavia), and from Israel, R. Vital (Shenkar College of Tel Aviv). In 2016 the campaign was directed by S. Bertocci and was coordinated by M. Bercigli. (University of Florence). For further information please refer to (Bertocci, Parrinello & Vital 2013; Bertocci, Parrinello & Vital 2014; Bercigli 2016).

Figure 5. Planimetry of the site, oriented and referenced according to Israel Transverse Mercator (ITM) coordinates.

dated with the contribution of the new survey performed (Figure 3).

After a careful planning phase, a laser scanning was performed using two different types of instruments: a Leica C10[4] laser scanner was used for the bulk of architecture and for the survey of the (largely empty) central part of the plateau since this instrument has a greater range; a Z+F Imager 5006h[5] laser scanner used mainly for the "casemate-wall." Through the use of various target types, like paper targets, it was then possible to record, in the Leica Cyclone software, the data from the two lasers in a single point cloud. The C10 laser scanner also acquired reference points for referencing the database according to a GPS coordinate system. The total number of laser scanning stations is 617, distributed equally across the archaeological site and within all individual spaces. Figure 4 shows the progress of the three laser scanner campaigns.

The 3D database consisting of the point cloud has allowed the extrapolation of 2D drawings, so as to obtain a horizontal plan of the site updated in 2015 and referenced with the GPS system. This was performed through the Leica Cyclone software, setting the parameters of Display in "elevation map" to display coloured areas every 5 meters according to the different altitude, with the 0 m height set on the plateau of the site and corresponding to the elevation 0 m a.s.l. Subsequently, orthoimages were exported and imported into Autocad so as to "trace" the point cloud to get a CAD drawing.[6] The final drawing represents a general planimetry at the large-scale of the archaeological site but does not contain all details of individual spaces (Figure 5).

Concurrent with the laser scanner campaign on the plateau, the photographic acquisition of all inner (architectural) spaces and the external part of the plateau was carried out so that the entire site could

4 Leica Scan Station C10 is a TOF (time of flight) scanner that acquires 50,000 points/sec, with a minimum range of 0.1 m and maximum of 300 m, with a field-of-view 360° horizontal and 270° vertical.

5 Z+F Imager 5006h is a phase-shif laser scanner that acquires about 1.000.000 points/sec, with a minimum range of 0,4 mm and maximum of 79 m, with a field-of-view 360° horizontal and 310° vertical.

6 For more information about the methodology please refer to (Bertocci, Parrinello & Vital 2013; Bertocci, Parrinello & Vital 2014; Bertocci et al. 2015).

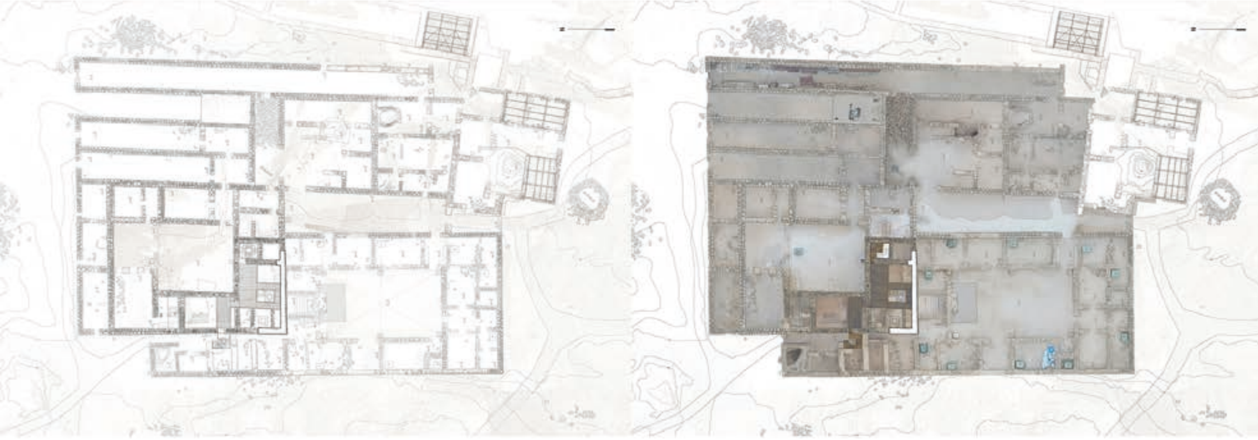

Figure 6. Detailed planimetry of the Western Palace.

be reconstructed photogrammetrically. These Structure from Motion (SfM)[7] survey techniques have allowed us to produce 3D models used for various purposes. Specifically, it was possible to set the same laser scanner point cloud reference system, then orient and scale all models to obtain information and details that can be integrated with the previous 2D drawing.

This led to the acquisition of thousands of photographs and in particular about 850 for the exterior only. In fact, it was not possible to acquire the external part through a laser scanner due to the morphology of the mountain and the impossibility of creating a closed polygonal path due to the cliffs. During the survey campaigns, two main methods of capturing photo sets were used: close-range photogrammetry and aerial photogrammetry (middle-range). The first instrument used was a Phantom II drone with camera. The flight speed was about 15 m/s and the installed camera was a 12 megapixel GoPro H4 that shoots up to 30 fps. This allowed us to take pictures from above and to obtain a 3D model of a large area, thus providing a basis for the integration of other detailed 3D models. Regarding close-range photogrammetry, two instruments were used: a Nikon D3000 10.2 megapixel digital camera and a 18.2 megapixel Sony Camera with the 3D-Eye system[8]. Photo alignment and calculation processes were made using Agisoft PhotoScan software, and the next step of aligning the different point clouds produced through the various survey tools took a long time. At this stage of the work, the organization of the acquired data and the precise cataloging of photographs were of paramount importance, as the data archive obtained was so vast.

The work proceeded by exporting the clouds produced by Agisoft PhotoScan and importing them into Rapidform to be able to extrapolate numerous sections in an automatic way. These were embedded in a CAD environment within the large-scale design in order to complete the 2D drawings in detail, portraying and representing each individual element in the rooms (stones, stairs, railings, mosaics, etc.). The major advantage of 3D models made by using SfM techniques is to be equipped with high definition textures; CAD drawings can therefore easily be integrated with the representation of the colour (texture) of artifacts and spaces (Figure 6).

Virtual Reconstruction: The Case Study of a Mosaic

This section reports on a case study of the Western Palace. This is the largest building of Masada, which stands on the west side of the cliff, near the Roman ramp and consists of three large main bodies. Here, as in the rest of the site, Laser Scanner and Photogrammetry surveys were made. 7020 photographs were taken and each single space has been described and cataloged through .raw[9] and .jpeg format photos.

7 Image-based surveying techniques allow the reconstruction of point clouds and three-dimensional models using the photographs (Remondino 2011; Remondino and El-Hakin 2006).

8 The 3D-EYE System provided by Microgeo s.r.l consists of a telescopic stick extending up to 13.5 m. A Sony digital camera is installed on it and is possible to control the orientation of the camera by a tablet. This way is possible to take high-definition photos from above.

9 A .raw file is an image generated by digital cameras and it contains uncompressed, raw image data that can be adjusted

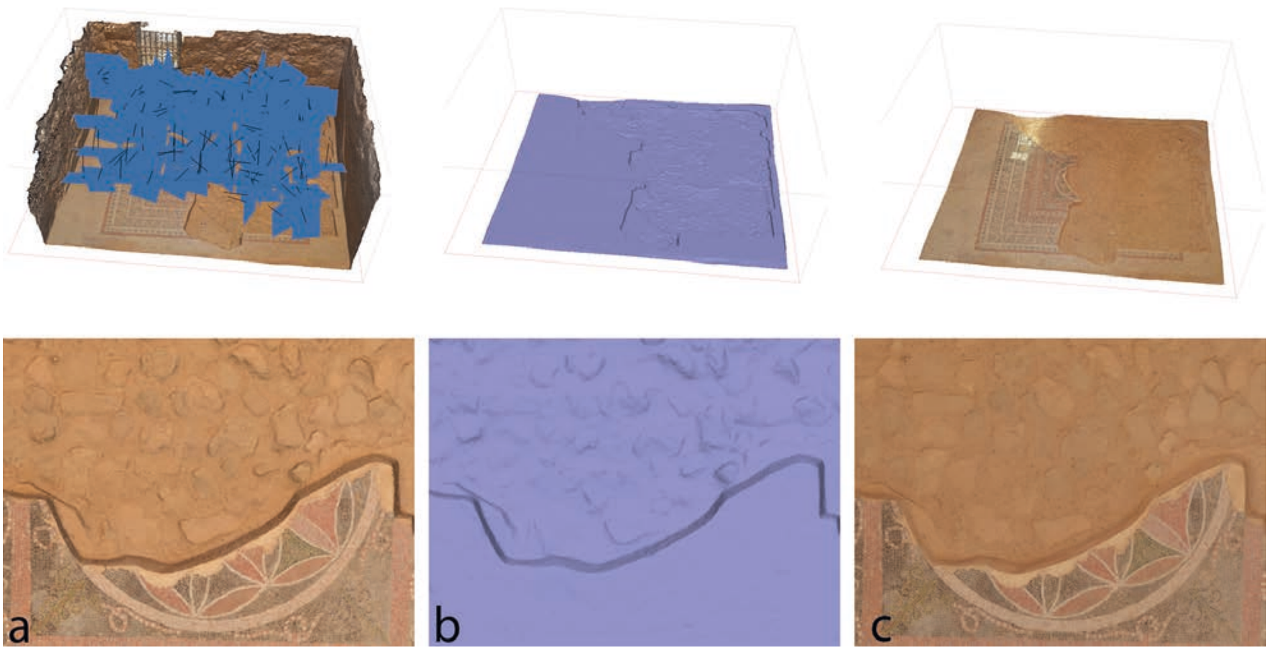

Figure 7. Figure shows 3d model realized through the use of Agisoft PhotoScan software. This model has a high definition texture and you can see above the details (orthorectified view) A: dense point cloud B: Mesh visualization C: Textured visualization.

The large number of photographs produced at the time of acquisition has prompted a structured data archive. During the photo shoot there were no special light arrangements, so they were later corrected using the .raw images.

Following all the photogrammetric processes, a detailed 3D model with a high-definition texture was obtained and some considerations were made on some parts, with a particular regard to a mosaic, which has only been partially preserved to date. An in-depth study was done on this mosaic at the entrance of the Hall of the Throne of the Western Palace. A total of 172 photos were taken and Agisoft PhotoScan (Figure 7) was used to obtain a point cloud and a high-poly mesh of about 1.5 million polygons with a high definition texture. Thanks to the targets previously set as reference points and thanks to the acquisition of their measures (reciprocal distances), the model has been scaled, rotated, and translated in the correct way. Thus, it was possible to export an orthorectified image with the mosaic design in true size. On the basis of these drawings, it was possible to obtain the exact geometry of each element. Following an in-depth study of the unit of measurement and comparisons with other known references, appropriate considerations have been made for the digital reconstruction of the mosaic.

Inside Masada's Western Palace, there are mosaics in the opus tassellatum technique which evidence the strong Roman influence that is present in the Herodian architecture (Netzer 1991:249-263). Analyzing compositions and geometric motifs, it is evident that the canons of the Greek-Roman tradition are perfectly followed. In antiquity, linear measures were related to the human body and in the Near East the fundamental unit was the "cubit" which remained the most used measurement system in the Mediterranean throughout the ancient period until the Roman era when it was replaced by the "foot." The cubit is an ancient unit based on the forearm length from the tip of the middle finger to the bottom of the elbow.

The geometries of the mosaic at the entrance of the Hall of the Throne of the Western Palace were analyzed for the "measure" that was supposed to regulate the composition. It turned out that the module used seems to be the 52 cm "Egyptian Royal Cubic." The mosaic is 6.5 cubits by 6.5 cubits, and concentric frames and individual geometric decorations continue to follow the original form (Figure 8). Before proceeding with the digital reconstruction of the mosaics, the group was concentrated on the materials, the colours, and the comparison with other "peb-

for exposure and white balance using software that supports the format.

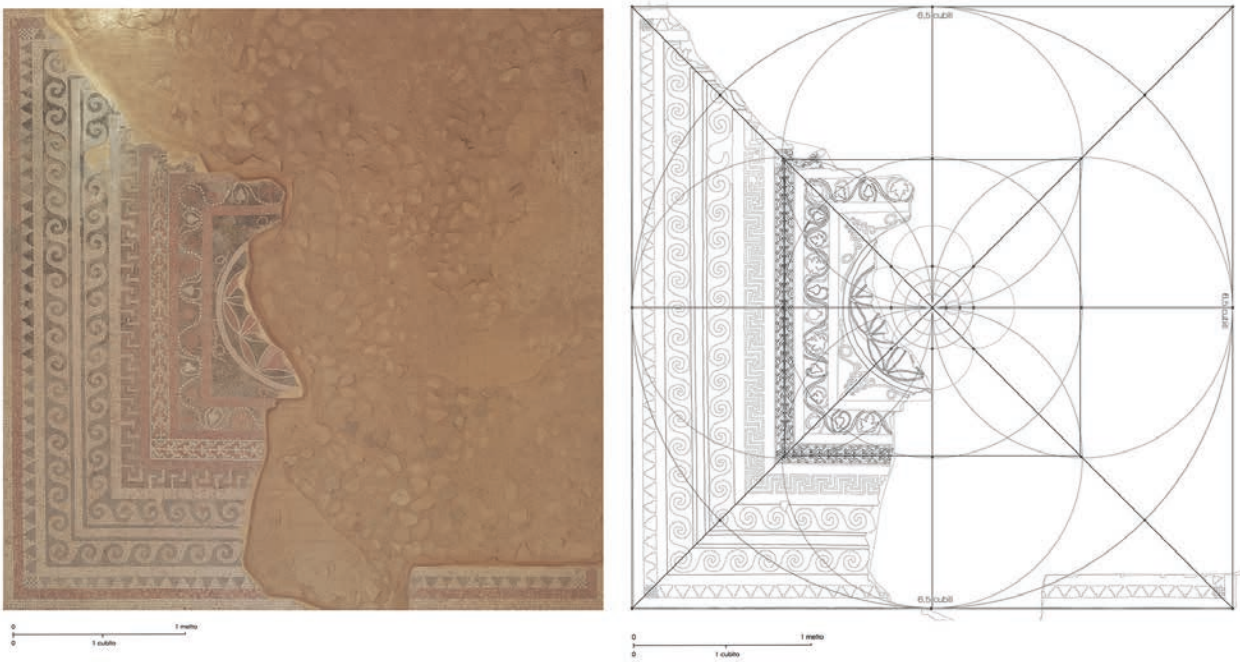

Figure 8. Figure shows the mosaic in the orthorectified view. From here, it was possible to proceed with the study of geometry and measurement in order to reconstruct its original drawing.

ble mosaics." The mosaic discovered is adorned with a geometric motif, very common in the Hellenistic world and which was mainly common on the island of Delos in the first half of the first century BC. In the center there is a decorative motif particularly associated with Jewish art, such as stylized branches of olive, pomegranate, fig leaves, vine leaves, and other natural themes (Yadin 1968:119-120).

Thanks to these studies and the procedures described above, it was possible to proceed with the hypothetical reconstruction of the mosaic, continuing the geometric design and completing the representation by coloring the "tiles" (Figure 9). In the end, the reconstructed 3D model was inserted in a virtual 3D environment to be displayed digitally in its original (albeit reconstructed) form.

Conclusions: The Possibilities of Using the Database

Nowadays, 3D models are increasingly used in the field of Cultural Heritage, even if they are constantly supported by traditional 2D graphic systems. 3D models, as well as providing design support, are important for permanently recording the shape of existing architectural works and artifacts, in order to achieve those for future generations. 3D models, therefore, have become an important 'tool' of the discipline for representation, useful for the construction of virtual scenarios, as well as for the valorization and dissemination of the heritage-related data.

In the case of architectural or archaeological complexes of a certain size, virtual models and related information become part of a museum system that are set up as real museums where the visitor is driven to become part of the narrative itself. The range of products through which you can configure a 3D digital system (video games, 3D model prints, web sites, AR applications, etc…) allows different approaches to representation, re-evaluating their limits, goals, and expressive potential. Virtual representative systems allow one to develop a more participatory and knowledgeable learning pathway and are able to increase the interaction between the user and the heritage-related information. In the case of the Masada fortress, the intention is to reproduce "virtually" the archaeological site in its entirety, exploiting the potential of VR and AR so that it can create multimedia content that can be viewed directly on the archaeological site through various devices, and at the same time can be accessed through PCs remotely. The appealing look and appearance of interactive 3D models and content, in this case, is more important than the metric accuracy of the work. Here is an example of the display of the Western Palace mosaic, accu-

Figure 9. The drawing of the mosaic cad geometry has been reconstructed and colored using a palette of colors derived from the study of the colour of the existing mosaic portion, comparing the colors of the other mosaics of Western Palace.

Figure 10. In the image, a rendering of the current status of the mosaic is observed. You can import the 3D model into software such as Unity 3D or Unreal Engine to make it interactive and associate extra content with some sensitive points to interact.

rately detected from material point of view, and its reconstruction (Figure 10). The greatest challenge in the development of a procedural way for the realization of effective virtual platforms is to seek representative way to understand and at the same time valorize and communicate the Heritage.

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Credits

The author of paragraphs 1, 3 and 4 is Stefano Bertocci; the author of paragraphs 2, 5, 6 and 7 is Monica Bercigli.

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3D Models of Architectural Remains in Archaeological Context: Visualisation as a Tool in Interdisciplinary Research of the Polish Archaeological Mission in Kato Paphos on Cyprus

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Abstract

The aim of the paper is to present the usage of different methods for obtaining 3D virtual models in order to document and better understand features of various kinds of data collected during excavations of the Polish Archaeological Mission of the University of Warsaw at Kato Paphos in Cyprus. During several recent seasons of excavations we tested a few methods of generating 3D spatial data, among others the image-based modelling and the structured light 3D scanner. As an interdisciplinary group of architects and archaeologists we used them for different kinds of objects: from relatively small pieces of architectural details and sculpture (e.g. fragments of columns, cornices, altars, etc.), through archaeological trenches to fragments of bigger structures and edifices. Most of the objects, independently of their size and scale, belonged to architectural remains. The comparison of methods and workflows with spatial data on the field helped us to find the best solution for multidisciplinary studies on the archaeological site of the Greek and Roman residential settlement in Kato Paphos.

Keywords: image-based modelling, archaeological decoration, Cypriot capitals, computer anastylosis

Introduction

This paper discusses how visualisation is used as a tool for studying architecture. Creating a virtual reality model of buildings has a very long tradition, especially when we consider traditional methods such as axonometric or perspective drawings showing hypothetical reconstructions of places, cities, dwellings or buildings that no longer exist. This kind of tool usage is one of the oldest and most basic applications of visualisation.

However, the use of 3D modelling as a recording and reconstruction technique has exploded in the last few years, so much that it has almost become a basic tool for modern archaeological projects. In this paper we present the way we use 3D models to document fragments of preserved architectural decoration in combination with long-used, traditional methods. We focus specifically on how visualisation might be used not only to generate views and models of non-existent architecture but to analyse preserved fragments of architectural details.

Archaeological and Historical Context

The examples of the architectural decoration we discuss come from the ancient city of Nea Paphos on the south-west coast of Cyprus. The city developed mostly during the Hellenistic and Roman periods and became the capital of the island. Most of the blocks were discovered in the southern part of the city where its residential quarter was located. There are relics of several extensive edifices dated from the Late Classic period till the Late Roman period (4 century BC – 5 century AD). The city was destroyed many times by earthquakes, and the present state of the architectural structures is a result of natural catastrophes as well as the activity of the squatters in very late antiquity. The remnants of the architecture take a form of the lower parts of the walls preserved up to the height of approximately 0.5 m and rubble filling the interior of the rooms, courtyards and streets. The rubble consisted among others of many fragments of architectural details.

Methodology

Most pieces of architectural decoration have no direct connection with particular buildings and are heavily destroyed[1]. The selected, most valuable fragments have been documented since 1970, primarily using the traditional methods and recently with diverse methods of obtaining the 3D models. The traditional way of documenting the architectural decoration was based on drawings. The greatest disadvantage of this method is the necessity of simplifying the drawings, which means that while preparing them one must reduce the view of the object and basically the drawings become an interpretation not a complete documentation. It certainly has its benefits, like presenting the merits of the objects, but at the same time it is possible to overlook some of their important but not obvious and less visible geometric features.

Primarily the 3D modelling is used to improve and contribute to a process of ongoing archaeological investigation and a post-excavation analysis. Recently it has also become a very important method of visualizing cultural heritage: original objects are replaced in Virtual Reality by interactive 3D models, which makes them more accessible and prevent an original structure from being damaged during the analysis process. That is why we started to document the most important architectural details with digital techniques for visualisation and reconstruction.

We used two methods to create the 3D documentation – a handheld 3D laser scanner and close-range photogrammetry. For the purpose of virtual reconstructions, mesh models with a texture were combined and fixed basing on their geometry in external software. The first method was based on the Artec Eva 3D scanner and the supporting software. We had some problems with the usage of the equipment especially in the full sun – the device could not work in sharp light with deep contrasts, a disadvantage pointed out by many scholars (among others Davis et al. 2017). That is why most of the blocks lying in an open area that could not be transported into a roofed or shady space could not be documented with this tool. The second disadvantage was the lack of compatibility of the software with other programs we use to create documentation of the material, another feature often mentioned by other researchers (Gonizzi Barsanti, Remondino, & Visintini 2013: 147; Manferdini et al. 2008: 221). The obvious inconveniences of the scanning method were also the necessity to carry extra equipment – the scanner – and the cost of the device. Both flaws have been widely documented in the research community (e.g., Davis et al. 2017; Gonizzi Barsanti, Remondino, & Visintini 2013, Manferdini et al. 2008).

The drawbacks of the hand-held 3D scanner were particularly striking in comparison with the close-range photogrammetry. For this we used a standard DSLR camera (Canon EOS 6D with 24-100 mm lens) that was also used for regular photo documentation. The image–based modelling is a commonly used method to acquire 3D measurements from multiple views (Remondino and El-Hakim 2006). In this type of modelling we can distinguish close-range photogrammetry as a ground-based technique used to obtain the 3D coordinates of an object from multiple photographs (Matthews 2008: 11-12). For this purpose, we used Agisoft PhotoScan.

3D spatial data are generated from a photogrammetric processing of digital images taken from offset positions, which allow an overlap of around 80% per pair of photographs. The processing steps of matching across the photos in the first stage is based on detecting overlapping points. Points that do not have a disturbed viewpoint or lighting variations allows the software to generate an identification for each point that is relayed onto its local neighbourhood. In the next step, these identifications are used to detect connections between the photos to align them. To deal with the intrinsic and extrinsic orientation parameters of the camera grid algorithms are used to estimate the camera position and then improve

1 More than 800 pieces of architectural decoration have been discovered only on the area under the supervision of the Polish Archaeological Mission. It is very difficult to estimate even approximately the number of such fragments in the whole ancient city of Nea Paphos.

Figure 1. The blocked-out capital from the House of Dionysus – a virtual anastylosis (by A. Kubicka).

the results using a bundle-adjustment algorithm[2]. In the next phase of the workflow, the dense surface is reconstructed where a few algorithms are available. Precisely, height-field methods are used for pair-wise depth map computation, whereas an arbitrary method is based on a multi-view approach. At the last stage of workflow texture mapping is carried out where a surface is parameterized by cutting it into smaller pieces. After that source photos are blended to form a texture atlas[3].

Required conditions for the use of the close-range photogrammetry are not as strict as far as distance and light are concerned as compared with a hand-held scanner. Some of the pictures of architectural details were taken in the open space because the items were impossible to transfer. It did not influence the precision of the mesh model, however the texture in some cases had to be corrected. The ease of mobility of the close-range photogrammetry allowed us to document several examples of a very specific type of architectural detail: the so-called blocked-out capitals (Figure 1). These details are found in different, distant from one another, archaeological sites of Cyprus. Therefore, you can compare them from different sites with the 3D models.

The reconstruction of the registered element shape was the second part of the 3D documentation workflow. It is based on the combination of two software programs: Agisoft PhotoScan and Z-brush. The synergy of these programs gave us far better results in terms of mesh and texture results for the reconstructed architectural details.

Agisoft was used to create a detailed geometrical model and its texture which then were edited and reconstructed in Z-brush. This workflow is very useful for editing small objects like architectural details. The diversity of tools for sculpturing allows geometrical precision of architectural decoration as well as the reconstruction of the original texture of the stone surface. The combination of the two programs provides the opportunity to obtain a very detailed geometry of the architectural decoration in Agisoft PhotoScan and to project some crucial features of the objects' form in the mesh reconstruction in Z-brush. These two software packages are compatible in terms of the type of exported and imported files. We can export files from Agisoft as .obj with a texture file and then

2 Bundle adjustment is usually used as the final step of every feature-based 3D reconstruction algorithm. It amounts to an optimization problem on the 3D structure and viewing parameters.

3 Technical information based on a description of Dmitry Semyonov on May 03, 2011, AgiSoft LLC, source: http://www.agisoft.com/forum/index.php?topic=89.0.

Figure 2. The Corinthian capital from the so-called 'Hellenistic' House: the traditional drawing (by S. Medeksza, 1989) and the 3D model (by A. Kubicka, 2012).

import it to the Z-brush. After some changes or the reconstruction of a mesh model or its optimization, the model can be easily imported back as a mesh to the original Agisoft file and the texture may be created once again, and then if it is necessary edited again in Z-brush. Missing data caused by inaccessible parts of architectural objects create holes in Agisoft mesh models. They can be interpolated automatically in the software. A more geometrically accurate effect can be obtained by sculpturing missing parts in Z-brush. Agisoft allows us also to create 3D pdf files, which are easily accessible and do not require any specialized software to view.

Results

The received 3D models enabled us to conduct very detailed analyses of the pieces regardless of place and time. The differences between the traditional drawing created by using traditional methods from the late 1980's and the orthographic view obtained from the 3D model can be observed by comparing the almost complete Corinthian capital from the main courtyard of the 'Hellenistic' House. The precision of the second method of the documentation is incomparably greater than the first one. It is especially important with fragments characterised by very complex, ornamental decoration, like the capital[4] in Figure 2. In the case of the Corinthian order, the delicate floral decoration of the capital is particularly important as it allows us to establish the estimated time or area of its creation on the basis of its similarity to a certain group of such capitals when its connection with a particular building or structure is uncertain or impossible to establish. This particular Corinthian capital shows a clear relationship with the Alexandrian Corinthian capitals type I and II, which is very important information that helps us date the structure to which the element belonged[5]. As mentioned above, many architectural details from Nea Paphos lack a reliable archaeological context, so the ability to estimate the time of their creation is extremely significant, even with a considerable margin of error due to the judgment conducted only on the basis of formal qualities.

Visualisation of architectural details also allows us to analyse forms that are more complex or more difficult to document, especially with the usage of a traditional, flat drawing. For example, the so called blocked-out capitals, or Nabatean capitals, belong to the characteristic type of the architectural decoration from Nea Paphos. The one presented here was discovered in the House of Dionysus (Figure 3). This kind of very specific capital is widely known from Petra in Jordan, but it also appears in Egypt and Cyprus. At a first glance the element seems very simple, almost devoid of decoration. But this is just a first impression that is misleading, as the capital is characterised by complex although delicate curvatures of the side surfaces.

It is very difficult or almost impossible to present its complete form using traditional methods – the superficial simplicity of the shape and the lack of ornamental decoration leads to very simple vector drawings, which do not reflect the real complexity of

4 Besides obvious differences resulting from the various methods of documenting, there are dissimilarities due to the time passage and exposure to the external conditions, e.g., the lack of one of the corners.

5 It is an example of the so-called Alexandrian decoration known first of all from Ptolemaic and Roman Egypt, but also appearing in Cyprus, which proves strong relations between the Island and Egypt.

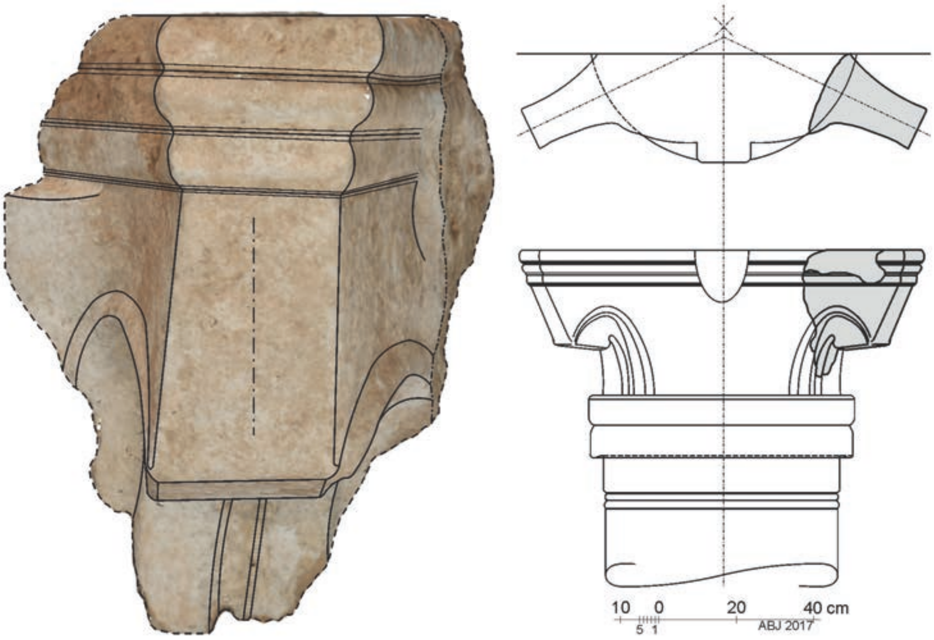

Figure 3. The twisted corner of the blocked-out capital from the so-called 'Hellenistic' House (3D model by A. Kubicka) and the hypothetical reconstruction of the whole capital of the engaged column (by A. Brzozowska-Jawornicka).

the form. The image-based reconstruction allows us to observe and study the spatial aspects of the capital very carefully as well as to document all the damaged and deteriorated parts[6].

On Cyprus this type of the capital frequently appeared as a part of the engaged columns or pilasters. Such types of supports influenced the shape of their capitals – they usually took the form of only a half of its standard form with just two corners (instead of four in a classic capital). These corners were also slightly different from the original version – they were twisted towards each other (see Figure 1). The majority of the preserved Cypriot blocked-out capitals are heavily destroyed, many were found in fragments – usually only the corners survived. In such cases the twist of the corners can be easily overlooked and is very difficult to be documented by a traditional method. The evident advantage of the 3D model is the ability to look at the object from different angles, which increases the possibility of noticing even small details.

Missing some of these important but subtle features may in turn lead to an incorrect reconstruction of the whole capital, and consequently the wrong support (e.g., a free-standing column instead of an engaged column or a pilaster) and moreover a mistaken structure (a portico instead of a pseudoportico). A false interpretation of a relatively small piece of the architectural decoration might cause a completely inaccurate reconstruction of the important part of the building.

The visualisation allows us to examine such a piece very carefully regardless of time and place. The possibility to study the object without the pressure of time (constantly present during excavation seasons) reduces the probability of omission of some important features and consequent misinterpretation errors. What is even more important is the compilation of visualisations of several pieces that allows us to compare them (Figure 4). These comparisons are crucial when there are different variants of the same type of object at some distance from one other and their comparison in situ is impossible.

In addition, the combination of the potentially matching fragments enables us also to create reconstructions – the presented blocked-out capital consists of three pieces lying in distant places but originally belonging to one element– difficult to gather in one place and impossible to check whether they physically fit together. The computer comparison of the 3D elements allows us also to conduct a virtual anastylosis before the physical one or instead of it, if the real one is not possible to execute (Figure 3). This method may also serve as a way to create even more complex reconstructions of preserved fragments.

6 3d modelling and semantic classification of archaeological finds for management and visualization in 3d archaeological databases, p.2-3.

Figure 4. The comparison of the visualisations of fragments of the blocked-out capitals from Nea Paphos (by A. Brzozowska-Jawornicka and A. Kubicka).

Conclusions

3D modelling and reconstruction based on photographs as a methodology of archaeological and architectural research significantly improved the fieldwork and the post-processing of the collected data. The documentation especially may be prepared much faster in terms of the collection of measurements and geometry of the analysed objects. However, the 3D modelling should not exclude traditional methods of documentation based on orientated and scaled 3D models (Kimball 2016): creation of the orthogonal sections and views from the 3D model still ought to be verified on the site in order to exclude misinterpretations of the finds' features. We would also like to emphasize the necessity of the verification of hypotheses in the site – nowadays the 3D models can be observed either on a flat computer screen or as a 3D print. In case of architecture reconstruction, the later usually takes the form of a model in a smaller scale and hence is less precise. Both cases may lead to some mistakes in interpretation. On one hand, the implementation of this technology in most archaeological projects has helped to optimise a time-consuming process of measuring techniques but has not replaced archaeological and architectural interpretation which are still done in the traditional way but with 3D models as a base. On the other hand, the documentation based on post-processing of the 3D models allows us, in many cases, to notice more features of the analysed objects then while preparing the traditional drawing during fieldwork. We can alter the light and shadow parameter or hill-shading techniques changing the reflectance of the surface in virtual reality, which may highlight some of the analysed object's features invisible in situ.

There is also one more advantage of the 3D models worth highlighting as opposed to the traditional documentation: the later method is characterised by the tendency to simplify the drawing and to prepare it in field in a certain scale which inevitably leads to the reduction of the complexity of the documented object. There are no such imposed conditions in working with the 3D models which could be prepared in their actual size and orientation. The only limitation is the size of your computer monitor.

The wide usage of 3D models of architecture as an analysis tool is commonly known (especially ISPRS Journal of Photogrammetry and Remote Sensing e.g.: Faka et al. 2017; Alby et al. 2017). It may be applied to many diverse types of analyses; therefore, the choice of suitable method of 3D modelling is an essential element to achieve sufficient results, meet the goals of the project, which will correspond to an expected degree of measurement accuracy and enable further research on an object or a structure.

Moreover, it is crucial to take into consideration the site's environmental conditions and weather to implement an appropriate method. The choice of the method to obtain a 3D model depends on many factors, the most important from our point of view are mentioned above. In our situation, the close-range photogrammetry seems to be the best solution, especially for the recording of architectural details. However, we plan in the future to expand the project and to create a 3D model of the whole site as complete as possible using a 3D scanner – a better tool for that task. So, as many scholars have pointed out, it seems that a combination of diverse methods may be the best solution (Balletti et al. 2015: 215, 221; Gonizzi Barsanti, Remondino &Visintini (2013): 150; Manferdini et al. 2008: 222).

One more important issue is also worth mentioning here: namely some archaeological projects run for many years or decades. For example, our Mission has been working for more than fifty years at the site. It takes a lot of time to enter all the previously discovered data to the new database, regardless of the chosen method. In such a case constant cooperation between the old documentation and the new one is unavoidable and sometimes it may also cause some problems.

Some other advantages of the 3D models used in archaeology are worth emphasizing. The complex heritage policy of the Department of Antiquities in Cyprus assumes enriching the traditional institutions connected with the preservation of monuments such as Archaeological Parks and Museums with Virtual Reality. Our models may serve in the future as a starting point for a virtual platform for both visitors and scholars enabling to observe, analyse and interact with some objects irrespective of time and place. Such an application of the modelling was also mentioned in the subject literature of Balletti (2015): 218.

Another interesting and very promising idea is a repository or an archive of 3D models of the architectural elements (e.g. columns, capitals, architraves etc) which could help scholars more quickly and more accurately identify a single new object (Manferdini et al. 2008: 221-222; Torres-Martínez et al. 2015: 43). Of course, this method has its obvious limitations such as a wide variety of variants of the analysed elements, but it may, if reasonably used, facilitate the work of an experienced scholar, although it is a topic for discussion in another article.

It seems that analysing architectural decoration by means of 3D models is a technique that is becoming increasingly widespread due to its utility and the advancements of the software and computing power. It may bring new information to researchers that will be helpful to grasp the whole structure to which the decoration originally belonged. The ability to work with the material outside the excavation area and after the excavation season is an obvious but very important advantage of digital modelling. The usage of 3D models as a method of documentation of architectural details allows us to return to the examined object whenever and wherever we want to or need and to understand it better.

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Place: The Physical Embodiment of Collective Information

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Abstract

Many classic landscape archaeology studies use GIS tools to create a 'god's-eye' perspective, where the images they produce are views from above the landscape looking down, like 2D-maps or viewsheds. Instead, this work uses software applications that recreate contexts from an individual's field of view. These are seen as investigative aids for examining archaeological problems about people rather than just illustrating newly gained knowledge from serious scientific investigations. The first application (*Horizon*) uses topographic data and 3D-rendering techniques to create landscape views with visual depth. The second application, *Stellarium*, allows us to insert new forms of output from *Horizon* as well as high resolution panoramic photographs taken at archaeological sites. This paper demonstrates the new informative digital outputs and their interpretive uses.

Keywords: visualisation, panoramic visions, place, *Horizon*, *Stellarium*

Introduction

Many classic landscape archaeology studies use GIS tools to create a 'god's-eye' perspective, where the images they produce are views from above the landscape looking down, like 2D-maps or viewsheds. By contrast, this project is inspired by 'individual immersion models'. These are tools used to recreate contexts from an individual's field of view, the 'point of view' perspective or 'egocentric' frame of reference (Higginbottom in preparation). These are seen as investigative aids for examining archaeological problems about people (Hermon 2008), and have been shown to be a more applicable way to discover something about the way landscape was used. This is done by recreating contexts from the point of view of people, rather than only "illustrating knowledge already gained once serious scientific investigations have been concluded" (Forte 2008: 22). Specifically, these software applications allow us to visualise how the sky and landscape appeared together to people in the past, viewed from any chosen point in a real landscape. The first application, *Horizon*, developed by Andrew G. K. Smith, uses topographic data and 3D-rendering techniques to create landscape views with visual depth (Smith 2013). The second application, *Stellarium* (Chéreau 2016) allows us to insert outputs from *Horizon* as well as high resolution panoramic photographs taken at archaeological sites. Significantly, both of these applications offer visual investigatory tools of the day and night skies combined with real landscape information. We applied this newest approach to case-study sites recently visited in Scotland on the isle of Mull. In this paper, we focus upon the digital methods and tools used for this extension of our project. By creating a number of land-skyscape models this paper endeavours to further understand the reasons behind erecting standing stone monuments and what was special about the locations in which we find such monuments.

Background

From the Late Neolithic onwards in Europe and the British Isles, regardless of the actual differences in dates, a form of megalithic structure that was essentially fully exposed and open to public view appeared (Bradley 1998; Burl 1993; Richards 2013). These standing stones appeared on their own or with other monuments. The variety of accompanying and associated monuments is great, including megalithic tombs, cairns, cists and earthworks (Bradley 2012; Burl 2000), and their forms are often well-known and/or regionally defined (Barnatt 1989; Brophy et al. 2013; Burl 1993, 2000; Richards 2013). The dates of the accompanying monuments are various, being built before, at the same time as, or after the standing stones. In Higginbottom (in press) it is argued that *the enwrapping horizon is a crucial factor* in the locational positioning of standing stones. The horizon, then, along with the megaliths, are all part of the creation and designation of place. This occurs through the enclosure and demarcation of visual space, creating close and far away views. This is related to Bradley and Richards' notions about stone circles and henges and their connections to nature. In his *Significance of Monuments*, Bradley (1998: 116-131) specifically argues that stone circles were created with links to the wider landscape, in contrast to the earlier henges, the circular mounds of which would have restricted visibility. Richards' himself, offering an example, states that "[the Deepdale stones'] situation on the downward slopes, effectively 'within' the confines of the surrounding hills, recreates the image presented by the stone circles within the henge. Here monument and landscape fuse in a series of transformations involving concentric order and representation of the natural world" (Richards 1996: 203).

The work in this paper concentrates on architecturally simpler standing stones sites, like single standing stones, stone pairs, short stone rows and small circles found in western Scotland. The original project was designed to unearth the locational choices of their builders, the reasons behind these choices, and what these reveal about the belief systems of these societies.

To date, through the application of *Horizon* only, this project has discovered a quantity and persistence of two land-skyscape patterns at sites across western Scotland on the mainland and the Inner Hebrides. One pattern contains sites that have the closest and relatively highest horizons in the north. These are referred to as 'classic sites' because that was the first pattern recognized. This was the only pattern found on Coll and Tiree during the beginning of the landscape investigations (Higginbottom 2003; Higginbottom, G, Smith, A G K & Tonner, P 2015: 630-36). The second pattern has the closest and relatively highest horizons in the south. They are simply called 'reverse sites'. What is intriguing, is that these two patterns exist whether the sites are rows, pairs or single slabs or menhirs, or even small, low circles like Hough (CT7; Higginbottom 2015: 627). Further, as well as Coll and Tiree, such patterns have also been found to exist at likely Bronze Age sites on Mull and Argyll (Higginbottom in press; in preparation). More specifically, those sites with close horizons in the north, will have their most distant horizons in the south and vice versa for the reverse sites. Most importantly, it was repeatedly found across these regions, that the same astronomical phenomena could be seen to rise out of and set into the dominant mountains, hills or points, found in the same general compass directions at each monument (Figure 1). On top of this, it was statistically verified that the monument orientations towards these astronomical phenomena were not likely due to chance (Higginbottom et al. 2000). These analyses of orientation data supported an interest in the Moon at its most extreme rising and setting points that occurs every 18.6 years, both in the southerly and northerly directions, as well as the Sun at the winter solstice (WS) and around the midpoint between the solstices (Higginbottom et al. 2000).

Together, this evidence so far points towards ***consistent*** opinions ***about where and how to erect a standing stone monument***. The wide-spread application of these opinions indicates that something other than personal experience is at work. Or to put it another way, that the sum of such person-centred views typifies and illustrates the social or cultural view of a group or groups of people who erected standing stones.

The next step in understanding this creation of places through the locations and alignment of standing stones, was to determine the details of what people could actually see when standing at the monuments, concentrating on how astronomical bodies acted and specifically how the movements of the Sun and the Moon played out against the sky. Notably, for this, it

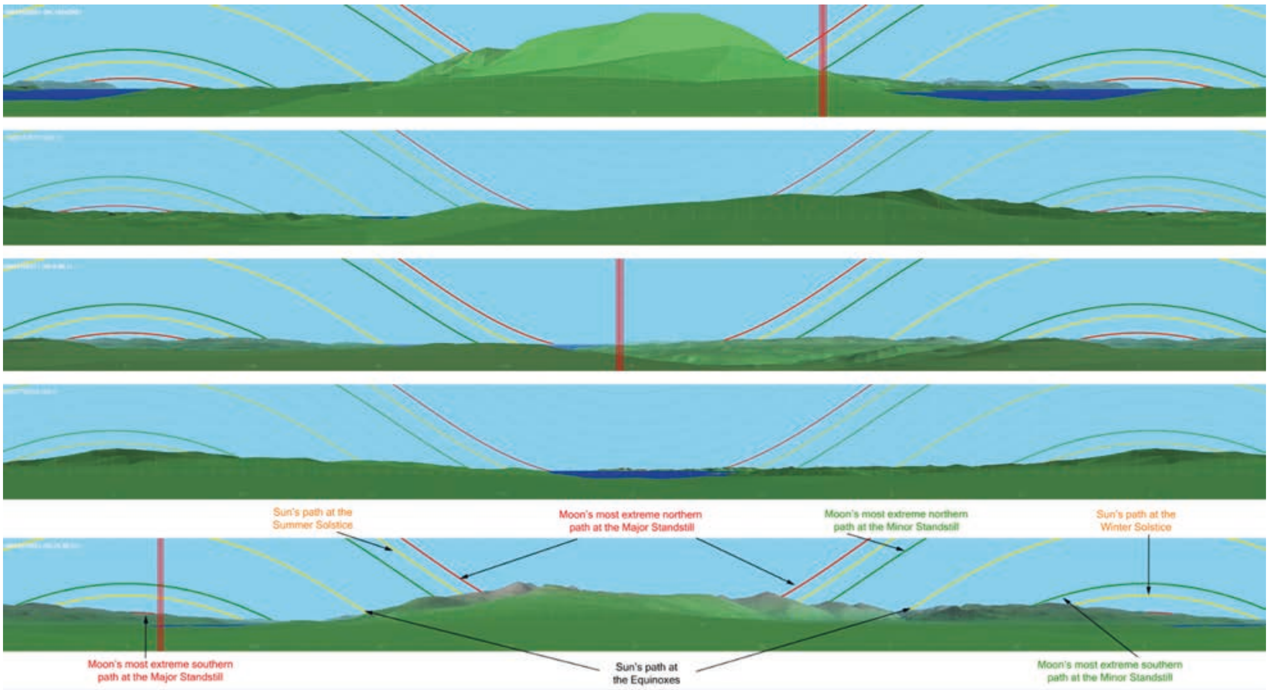

Figure 1. Examples of the two land-skyscape patterns found at sites across western Scotland. The top two and the bottom one are classic sites (Cragaig, Glengorm and Uluvalt), the third and fourth are reverse sites (Maol Mor and Cillchriosd). Each image also shows the representations of curved paths of particular celestial bodies seen from the location of the monument using coloured lines. The site of Uluvalt contains labels explaining which celestial path each line represents.

was important to know how the paths and phases of the Sun and Moon interacted, for the Moon's path is always within 5o of the Sun's path, and views of one affects the other, especially in terms of lighting and location. Whilst knowing such things provides more vital information on the visual experience of natural places, *comprehending* the visual experiences of each site requires more than this type of data. In the interests of greater comprehension and the communication of these things to others, creating a *narrative of first-person visual experiences* was chosen. It was found that using a narrative-based approach created revelatory texts and personal insight into the visions of the past. For example:

> It is summer … I can see that the differences between Sun's (and Moon's) rising and setting positions along the horizon are getting less and less each day. I now know that the great event of the summer Sun approaches, the summer solstice. Soft light is now continuous through the night and after the Sun drops below the horizon it is still light enough to carry out ordinary activities outside our family's dwelling for some hours. At this time, some of us travel to our designated place on our clan's western isle, to Gruline. At this place, we divide: some stand with the eternal Witness stone closest to sea (stone ML 16a), (some) with the mountain Witness stone (stone ML16b) and others stand nearby … On the marked day, all of us can see the Sun rising in the north-east and, with this, morning twilight passes. Those of us standing with the Witness of the Mountain (stone ML16b) can see the Sun *rise out of the dominant northern mountain chain and run along its edges for a short while* … As time goes by, … we later turn to face the west and northwards again to watch the Sun set *into the dominant range in the northwest*. However, it is only those of us standing with the Mountain Witness that are clearly directed *towards* the exact and appropriate setting position of the summer solstice Sun … by … the line that runs between the Witnesses of the Mountain and the Sea extending beyond the sea itself towards *the precise hilltop upon which the Sun will set* … (Higginbottom in press; technical corrections added here since draft of 'in press' paper, submitted and uploaded online to academia.edu).

We know, too, that the Sun and Moon's movements just below the horizon created various sky-light changes and glows and were clearly important parts of the visual landscape, though it is not really possible to comprehend exactly how they were seen or understood. It was further suggested that even these bodies' actions below the horizon were hypothesized by the builders of the monuments and the contrasts between that which was above and that which was below the Earth were relevant, primarily in terms of the concepts of nadir and zenith (Higginbottom in press). We will see that some of these unknown light qualities were clarified by our application of the digital tools below.

Digital Tools Used

For our reconstructions we use a combination of digital tools:

1. *Image Composite Editor*, a program to create panoramic (3600) images from sets of digital photographs (Microsoft Research Computational Photography Group 2015)

2. *Horizon*, which uses topographic and astronomical data along with 3D-rendering techniques to create landscape views with visual depth. Created by Andrew G. K. Smith of the University of Adelaide (Smith 2013).

3. *Google Earth* (Google Inc. 2017). Created by Keyhole, Inc. and further developed by Google Inc., it is essentially a navigable 3D GIS rendition of earth.

4. *Stellarium* (Chéreau 2016; Gates et al. 2016), a public domain astronomy software package that allows viewing day and night skies as observed from a given location on a particular date at a given time.

Image Composite Editor (ICE)

The procedure for creating panoramic photographs for each case-study monument runs as follows: first, a series of approximately 24 digital photographs is made at the site, spanning a full circle (camera: Olympus E-600, tripod equipped with a CamRanger turntable). The height of the camera was 1.50 meter above the ground, 2 meters from the standing stone in the direction of the alignment of the stone (if visually detectable). The series is stitched using ICE (version 2.0.3.0), resulting in panoramic images with a size of approximately 12.5 MB (22000x3000 pixels).

Horizon

The software was named *Horizon* after its original ability to calculate horizon profiles. Its primary aim is to combine topographical data with atmospheric and astronomical calculations to produce accurate three-dimensional landscape information to aid archaeoastronomical surveys and data analysis (Smith 2013). The two major functions of the *Horizon* software are 2D horizon profiles and 3D panoramas.

The horizon profiles are the apparent elevation of the horizon for a hypothetical observer located at a specified point within the landscape, sampled at regular intervals in azimuth around the full horizon, where the horizon is defined as the point with the greatest elevation in a given direction, which an observer would be able to see. Outputs of *Horizon* can be used for further analysis, which includes calculations of the distance and direction between the point of origin to all points on the horizon and the altitude of each of these horizon points.

The panoramas are rendered pictures covering a full 360 degrees from the viewpoint of an observer who is, as with the horizon profiles, located at a specified point within the landscape. Apart from the location, *Horizon* allows you to choose epochs, astronomical phenomena and dates far back in time. The results are far from photo-realistic, but they are ideal for visualising the topography of the landscape (Smith 2013: 5). Onto these landscapes are mapped the paths of astronomical phenomena like the sun on the longest day and the shortest day and those of the Moon at the times of its most extreme rising and setting points in its cycle. Relevantly, you can choose specific dates and time for the plotting of the paths of the Sun, Moon and even stars.

Google Earth

Through Google Earth one can view much of the earth in 3D. Google Earth produces landscape images of a somewhat less abstract nature than *Horizon*. Whilst the elevation data is not as accurate as that used with *Horizon* (see 'Data' below), it still produces some good basic visual models of landscape views. Its data includes elevation data including Shuttle Radar Topography Mission data, bathymetry data, as well as satellite and aerial images.

It is possible to use Google Earth to create 360-degree panoramic images from a location on Earth. Once you have chosen a location and are viewing it from 'above the Earth', you can 'zoom down' very close to the actual surface. When zooming in on such a point, Google Earth will automatically switch to 'horizontal view mode' so that you can create the panoramic images.

Taking screenshots at the chosen location every 150 results in a series of 24 images which are processed with ICE in the same manner as the digital photographs. This produces a final composite image of about 7500x900 pixels. The vertical height of the Google Earth images depends on the automatic switch and is more or less within a range of 50 m, but difficult to reproduce.

Stellarium

In its most basic form this astronomy software package enables one to view the night and day sky from any location on Earth (as well as bodies in our solar system). Essentially it renders 3D photo-realistic skies in real time, giving the option of choosing location, date and time. It is possible to pan around the landscape or to alter the field of view in terms of the amount of the horizon and sky that are seen.

Although most *Stellarium* parameters have mainly astronomical relevance, with *Stellarium* version 0.10.6 or later, the default landscape can be replaced. This feature enables the user to associate a specific panoramic image of a place with its set of geographical coordinates (i.e. the position from which the panoramic photograph was taken). When these coordinates are chosen, *Stellarium* will then show views of the sky combined with this panoramic image, resulting in a dynamic view with sunrise, sunset and night sky for the specific date and time chosen.

Most strikingly, the use of *Stellarium* can turn the whole observation exercise into an almost cinematographic experience through its video-like animation and 'frame rate' options. These create moving heavens over the landscapes from the point of *real time* motion to faster time frames, allowing to pick-up patterns of movement of astronomical phenomena more readily.

Stellarium supports several methods for describing landscapes. However, the *Stellarium* Dialog in *Horizon* currently only supports the Single Panorama (or spherical) method to export compatible 2D horizon profiles and 3D panoramas.

Combining Data and Software Outputs

What the current authors have done is to create a single comparative image for each site. This was done by stacking the 3D panoramas from *Horizon*, the panoramic photographs taken at standing stone monuments and the Google Earth panoramas, one under the other (Figure 2).

These simple stacked panoramas were much more informative overall as clear, easy comparisons and considerations could be made. Importantly, it was possible to line them up quite well in the horizontal axes, despite some minor differences in landscape feature placement.

The major underlying benefit of the 3D panorama models is that the shape of the horizon and the topography of the landscape can be seen all the way around the site, something photographs can rarely do, either due to tree or cloud cover. Overall, then, including a comparative 3D panorama is particularly useful when research requires detailed horizon or topographic detail. Further, it is likely that much of Mull was covered in open forest and that the horizons could be seen in the Neolithic and Bronze Ages (Tipping *pers. comm*. 2015, in relation to his work Tipping 1994)

However, the photographs are essential to understand something of the natural aesthetics of a place. The photographs give a sense of human scale and a comprehension of this, even though this is a panorama and does not represent an immediate human field of view. This is due to our general familiarity with objects (trees, fences, walls) in the photograph, as well as the objects allowing for height comparisons and possibly depth considerations (Kaufman and Kaufman 2000), letting us understand something of the scale of the place.

The second step involved the creation of 3D pan-

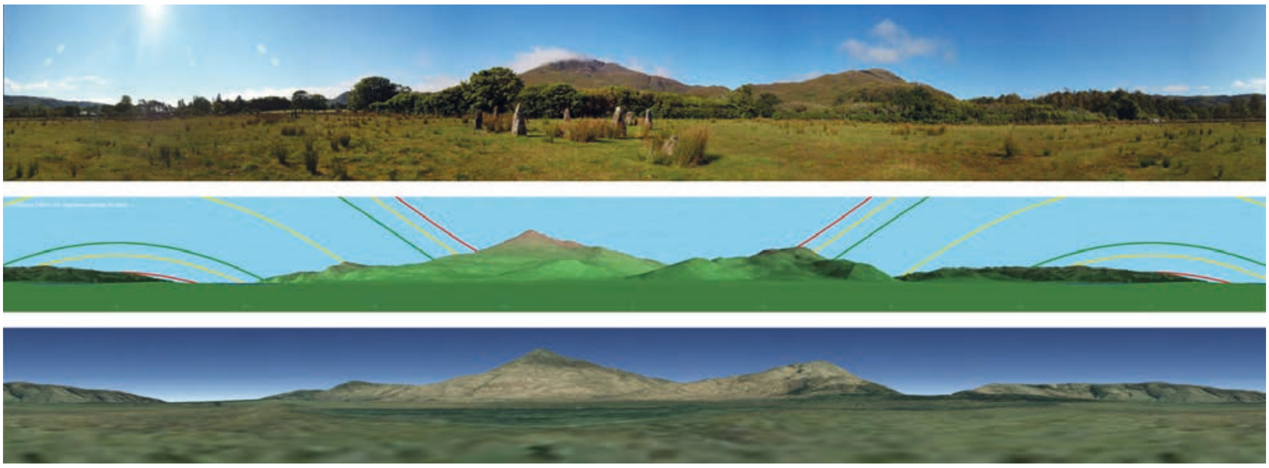

Figure 2. An example of stacking landscapes from different software outputs for cross-comparison purposes. This site is the stone circle of Lochbuie, Mull.

orama files in *Horizon* that work with the spherical projections in *Stellarium*, as well as the creation of panorama landscape photographs, from a series of photographs using ICE. Various conversion processes were required for their use in *Stellarium*. The panoramas, originally jpg format, had to be converted to png format because the upper part of the image must be transparent in order to show the sky from *Stellarium*, a feature that the jpg format does not offer. Standard photo processing software was used to do this, including the required scaling and aligning. These two digital outputs, then, allowed for two types of integrations with *Stellarium* – one a 3D digital model and the other a photographic capture of landscape.

Without a doubt, the import of panoramas into, and the running of, *Stellarium*, has transformed our understanding as researchers of place. Whilst *Horizon* can now produce stills of night skies on particular dates and at specific times, through *Stellarium* we can more fully comprehend what could actually be seen from these monuments with its moving pastiche of 24-hour skies that roll on continuously from one day to the next, in slow motion or real or accelerated time.

Having already gathered visual information from a combination of astronomical knowledge, the alignments of the standing stones and using the 3D landscapes, along with narrative, we already knew something of what could be seen at sites on Mull and other places in western Scotland in the past. With this combination we concentrated on the Sun and Moon (Higginbottom in preparation, in press; Higginbottom et al. 2015). Whilst our focus has remained on these bodies, the lightening effects in the sky and upon the land are much more fully realised by using *Stellarium* and even the paths of other highly visible celestial phenomena come into play.

Results

We will now describe and discuss what was actually seen in *Stellarium* at sites on Mull using example sites to demonstrate consistent or specific phenomena observed. This will be done via screen grabs that record screen animation, as *Stellarium* does not have any output capacity. Please note that the views we describe are at the times of the WS or summer solstice (SS) for 1500 BC, seasonal times of interest that were confirmed as relevant through previous research (Higginbottom 2003; Higginbottom et al. 2015; Ruggles 1984), but we could have chosen other times. The epoch of 1500 BC is in-line for the earliest dates of simple standing stone sites such as these in Scotland.

One of the most visually intriguing shared visions to be found at sites through *Stellarium* is the way prominent features on the horizon are backlit from the Sun just prior to rising or just after setting at the solstices, this is more prominent at the SS. More striking at some sites than others, this back lighting causes the entire horizon about prominent or distinct topographic forms at the ordinal directions of the northeast, northwest, southeast, southwest to glow, setting up the horizon area in one direction 'at a time' as a focal point, in stark contrast with the rest of the darker landscape. Watching as the Sun slowly vanishes in the northwest at classic sites like Lochbuie and Uluvalt, the intensity of the halo increasing about the northwest mountain as night pulls in, is very striking (Figure 3). Relevantly, it has already been shown that that these distinct topographic features placed in ordinal directions around the standing stones is likely to be a deliberate consideration (Higginbottom in press, in preparation, Higginbottom et al. 2015). This is because, at the times of the Moon's most extreme rising and setting, and those of Sun, these same bodies are seen to rise out of and set into these ordinal features from the purview of the standing stones. Remembering, too, that the orientation of the monuments to these same rising and setting points are statistically supported (Higginbottom et al. 2000).

As the night of the solstice continues, and the Sun moves further below the horizon, the halo of light above the horizon almost vanishes, then there is soft glow evenly distributed at and either side of true north (Figure 4). At sites like Lochbuie and Uluvalt, this is accentuated by the fact that north has 'been positioned' in the middle of a dip between two significant single, or sets of, peaks, as viewed from the monument (Figs. 3 & 4); Poit na h-I has a distinct change in slope at north. Notably, when at north, the Sun is at its maximum distance below the horizon. As midnight passes we can see the amount of sunlight increase and as we move towards dawn the entire mountain or hill in the northeast is backlit, and the rest of the landscape is still relatively much darker as the mountain or hill takes pride of place as the visual focus. This is the feature out of which the SS Sun will rise.

Another shared vision involves the brightest group of stars in Ursa Major (UMa). At this epoch, these stars of Uma sat within the circumpolar region of the sky as they do today, never rising or setting. This means, that almost no matter where you are at these latitudes you will see them. They are arranged in a curving shepherd's crook (Figure 4). There are distinctive views of these stars that occur at the WS and SS when you are standing at a monument. For example, at midnight at the SS these stars are positioned as a group horizontally low in the sky in the north, with Merak, the second star in the chain from the 'right', immediately above true north (Figure 4). At the WS, UMa is directly overhead of the viewer, at the zenith, but the group of stars making up Ursa Minor (UMi) – also a shepherd's crook-like but small-

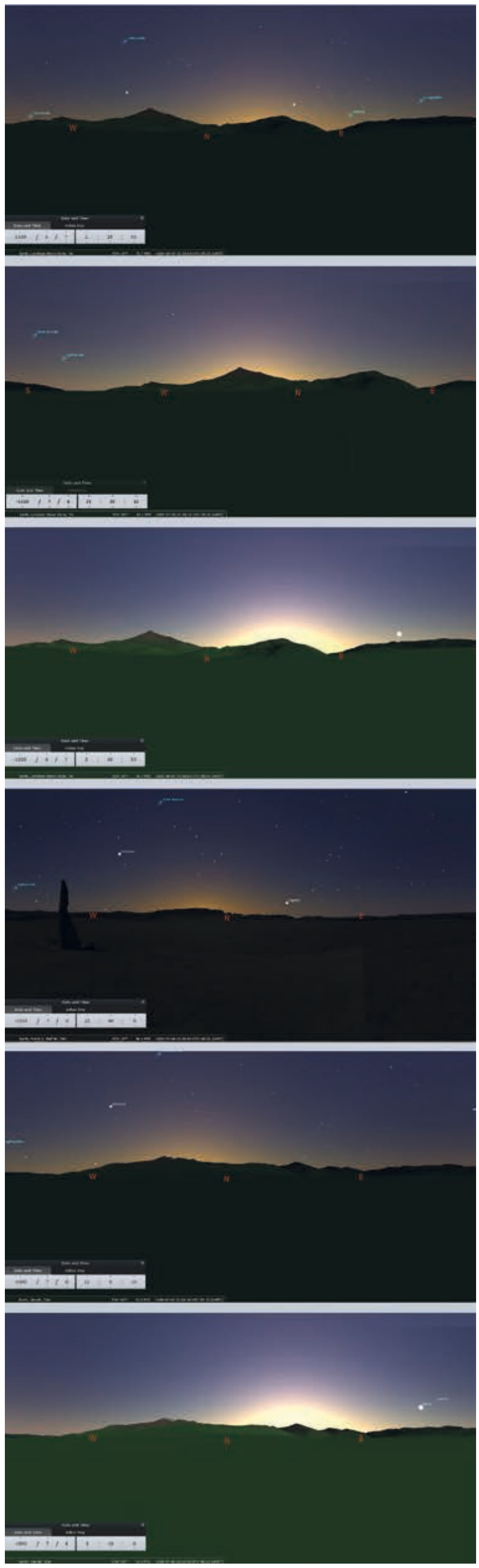

Figure 3. Illustrations of landscapes prior to sunrise and sunset at the summer solstice, where prominent features on the horizon are backlit from the Sun causing the entire horizon about prominent forms to glow. Sites names from top to bottom: the first three are from inside the circle of Lochbuie; the fourth is Poit na h-I. The last two show the highlighted mountain edges of Uluvalt. The Mercator projection in Stellarium was used for the creation of these images.

Figure 4. Striking instances of the sky lit at dead north. Note the dips in the horizon at North to accentuate light given out by the Sun at this time. The sites in order from top to bottom are: Uluvalt, Ardnacross, Poit na h-I, and Lochbuie.

Figure 5. Light and celestial displays at the reverse stone row site of Ardnacross (ML12) at the summer solstice as described in the main text.

Figure 6. Light and celestial displays at the site of Ardnacross at the winter solstice as described in the main text.

er, now sit low in the sky in same position that UMa occupies at the SS. At classics sites like Uluvalt and Lochbuie, this means that UMa phenomena at the SS will be located between the two prominent peaks of the northwest and northeast, which create a focal range. Other notable visions at the WS for all sites include the travels of Betelgeuse, where it sits right alongside or matches the Sun's path of the Equinox for this epoch. Similarly for Pollux, as it travels along the most extreme path of the Moon in the North. These travels can be seen for the entire period of 1550 to 1200 BC, which overlap those known dates for the erection of these simple standing-stone monuments.

As we can see from these examples, monument horizons shared particular traits affecting the shared views of the skies and the astronomical bodies. However, what *Stellarium* also demonstrated so well was how the individual nature of a site horizon would affect the overall astronomical show seen at each separate site: like what bodies are blocked in which direction and by which landscape and when. Therefore, these following examples are about the individuality of place within a shared system of collective information. As with the shared views above, these views are linked to particular epochs and times of the year. Due to the limits of space we will use just one example site, Ardnacross.

At midnight on the SS, as the Sun sits below the horizon at true north, the full Moon rises in the southeast slowly increasing the light of the midsummer night skies (Figure 5a). Standing two metres away from and in alignment with the southeast stone row, one can see this row *aligned to the Sun under the horizon* in the north *soon after midnight* (1:30 am; Figure 5b), the glow of the SS Sun's rays lights up the stone from behind. As the SS Sun rises higher towards the horizon in the northeast, more easterly, Venus has risen out of the slopes of the highest hill in the northeast (Figure 5c).

In the deep night of the WS, when the Sun is far below the horizon, the combined effect of dark skies and bright bodies in the sky is striking. A travelling full moon does little to diminish this night sky display whilst it is high in the sky, yet it is bright enough to lighten the landscape and the standing stones emerge from the darkness (Figure 6a). As the Sun then moves towards the horizon to rise in the southeast, the Moon moves towards the west-northwest to set and Capella sits at dead north (7:20 am; Figure 6b). Soon after this, the Sun rises out of a clear hill in the southeast. Standing in alignment with the stone row, this time looking south, *one is exactly aligned with the stones and the Sun as it sets at the WS*. Soon after the WS Sun has set (approximately 16:30), with the bright sun-rays remaining, Mars, Jupiter and Venus are heading westward, and the bright stars of Orion's belt rise in the east-southeast. At 16:40, and all at the same time, Mars sits above the cardinal point of south, Procyon sits above east and Altair sits directly west on the horizon itself. A little arc of stars line up with the arc at the top of the stone. Merak and Duhbe of UMa sit above the top of the stone, with much of UMa low in the sky at this time of day. Having such a number of prominent bright features close to the horizon draws the eye towards the horizon itself and when it is completely dark, at 17:30, Arcturus sits dead south and the full Moon rises in the northeast (Figure 6c). All this time UMa has been slowly turning and at 21:00, it sits vertically above the stone with the star Phecda of UMa sitting most centrally (Figure 6d; the projection for all these views, Mercator, has been used in order that both a higher and wider sky-view can be observed). The full Moon has lit up the land. These distinct views at an individual site occur at the same times as all of the other *shared visions* described earlier. Here we are seeing the marking out of the land and the marking out of astronomical phenomena. These inextricably linked goals create very specific visual effects.

Conclusion

This work explicitly uses the interaction and navigation of the spatial, temporal and thematic components of archaeological data to demonstrate how visualisation facilitates deeper insights into archaeological phenomena. The combined effect of these programs is to integrate quantitative capabilities along with different forms of visual interrogation. Whilst *Horizon* does not yet have photo-realistic visuals and time-lapse frame-by-frame animation, it has several advantages over *Stellarium*, including output facilities for data and images. On the other hand, *Stellarium* has allowed us to see visions in the landscape that are clearly linked to these latitudes and more narrowly, specific sites. For each monument horizon, whilst we already know them to strongly share some values in terms of general shape and the positions of the rising and setting Sun and Moon, are at different relative altitudes and not always in the exact same place. For those who have no or little knowledge of astronomy, and, therefore cannot imagine how the Sun and Moon's paths and cycles interact to create a narrative as that found in Higginbottom et al. 2015, *Stellarium* is invaluable.

The important thing, though, is not to apply *Stellarium* to one site and make conclusions about possible astronomical connections, without having done research into probable patterns with more certain data, such as the orientations of the same groups of site types, for instance. Otherwise, naturally, conclusions arising from the former approach will not be sound.

Through our use of new tools and our new use of available software we have come to a greater understanding of place as it was seen and experienced more than three millennia ago. The views of some of these natural phenomena may well have occurred by 'chance', that is they were not easily blocked out by a horizon as they were so high in the sky (such as the view of UMa). However, the fact that the monuments were located in areas that gave them clear views of skies in various directions meant these sights would be included; they clearly weren't located in crevices or narrow, steep-sided valleys. Also, those phenomena at the cardinal points, like the sun glow evenly spread above due North at midnight at the SS, are much more likely to have been deliberately included through the choice of the height of horizons in these directions. We surmise this because we already know that monuments were aligned to particular phenomena on the horizon and that other stone monuments were also often set up with a north-south axis, like the circles of Callanish and Stenness (Higginbottom and Clay 2016a). Further, we can see that sites were chosen with mountains or hills either side of north and south or with the same straddling north or south, with north or south sitting roughly centrally (Higginbottom et al. 2015; Higginbottom and Clay 2016b; Figs. 1,3,4).

The knowledge contained in locating, cutting, working and moving stone, in the understanding of the day and night sky and how the Sun and Moon behave together over time, and the two millennia over which they were built, point to a great deal of collectively held knowledge and activity. Past people related *notions of time* to the locations of the planets and the stars, effectively dividing up, and connecting, the night and seasons, with place. There is a natural inter-dependency recognised by the builders. It seems, then, that standing stones are landmarks for people in the past (MacKie 1988). They embody information about the landscape as these people saw and understood it, and therefore information is specific to the local setting and may not be applicable to any other setting or location (Higginbottom et al. 2015: 632, 634, 636). Standing stones are thus proxies for a single point of view but are a constructed physical embodiment of complex collective information (Higginbottom et al. 2015: 632, 634, 637, 640), similar to other monumental sites (Atakuman 2014: 6, 19).

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