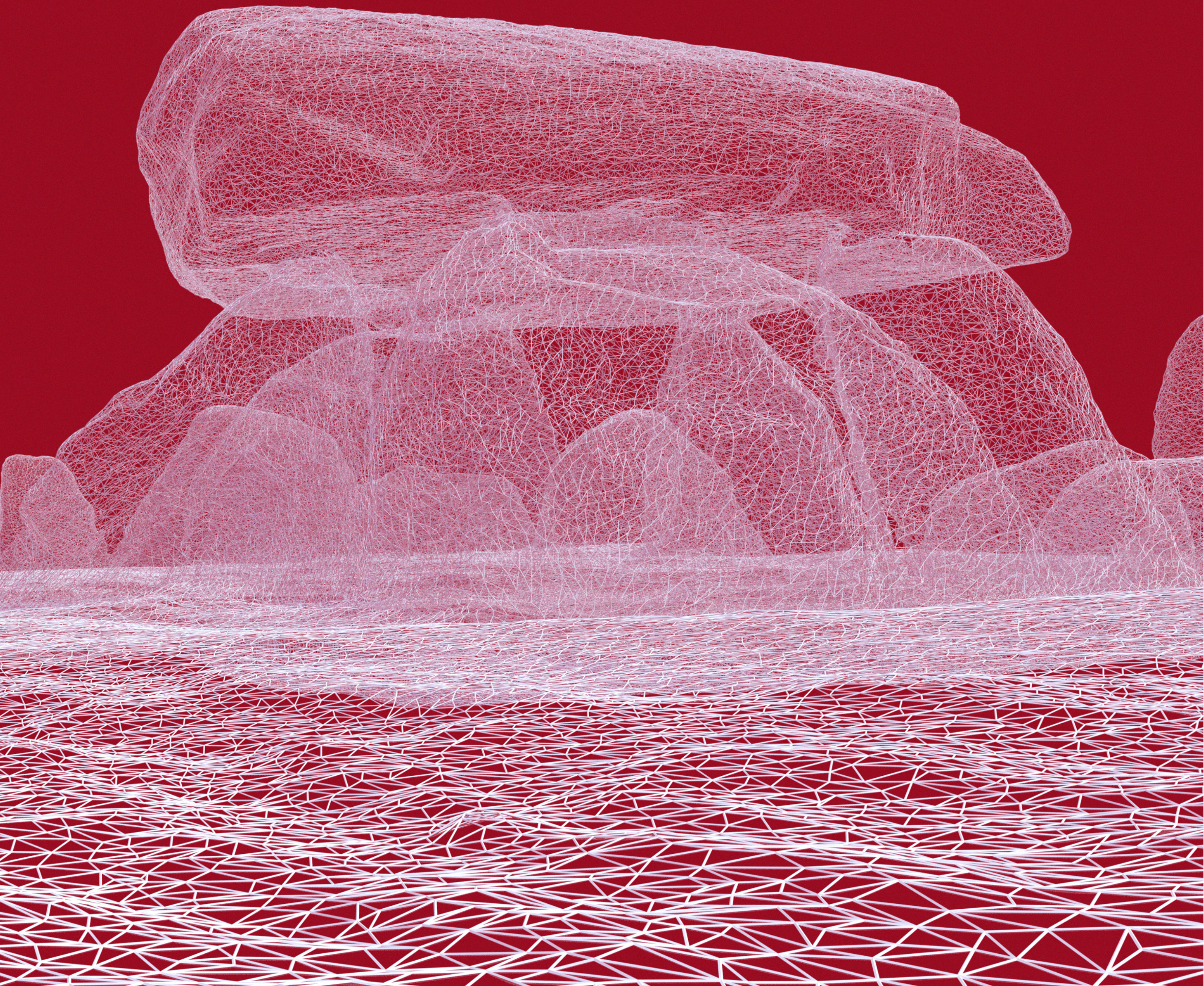
APPROACHING REALITY

INTEGRATING IMAGE-BASED 3D MODELLING AND COMPLEX SPATIAL DATA IN ARCHAEOLOGICAL FIELD RECORDING

Peter Jensen



Front cover: Wireframe model of the Neolithic dolmen "Påskær Stenhus"
(Graphics generated by the author using image-based 3D modelling).

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Introduction: Approaching Reality

Archaeological documentation practice is currently undergoing a silent revolution. Time honoured traditions are being replaced by new digital methods for excavation recording. Not only are the principles and foundations for archaeological documentation changing fundamentally, but this is happening with only scant attention to the consequences for how we secure and integrate our archaeological data. It is not the primary goal of archaeology to simply collect and store data, without bringing it to further use. Archaeological excavations should contribute to scientific research by producing high quality, detailed documentation within a larger conceptual framework which supports collaboration and interoperability. The same applies to spatial data - drawings, models and measurements - which tie together an otherwise seemingly abstract or even chaotic complexity of archaeological observations and interpretations. Yet spatial recording - both 2D and 3D - is severely detached from its textual information, despite the significance of visual representations for conveying and disseminating archaeology. Currently we are at danger of losing valuable data, as spatial excavation documentation is produced which is incompatible with current technical, theoretical and methodological frameworks and infrastructures.

This study represents a methodological investigation aimed at addressing existing challenges of integrating complex spatial data in archaeological excavation practice. These challenges combine issues inherent to the traditional abstraction and conceptualisation of the observed and interpreted archaeology (Hodder 1999; Hodder and Hutson 2003; Pavel 2010; Lucas 2012; Forte et al. 2015), with the epistemological and methodological paradigm shift related to the advent of digital image-based 3D recording techniques like Structure from Motion (SfM) (Pollefeys et al. 2001; De Reu et al. 2014).

The digital revolution in archaeology is perhaps most evident by the early and continuous adoption of Geographic Information Systems (GIS). Yet it is arguably the inability to manipulate three-dimensional data natively within common GIS solutions which constrains its full capacity as an Archaeological Information System (AIS). There are, however, more nuances to the issue and the three-dimensional character of archaeological data is not necessarily as profound, despite claims to the contrary (Harris and Lock 1996). While spatial data inarguably are at the core of all archaeological recording, the discipline is permeated by two-dimensional projections, which do not correspond to an ideal of three-dimensional recording. It is in fact debatable if archaeological documentation ideals are shaped by what is technically possible, rather than the opposite. Perhaps more than anything else, archaeological excavation methods are governed by and aimed for an end-goal of publishing and print on paper (Madsen 2003), and according to the prevalent methodology, top-down, two-dimensional projection is necessary to create the drawings and delineations which carry the archaeological interpretation. The paper media still dictates the way archaeologists record and document, and it affects the abstract data structures used for organising archaeological field recording. It may be interpreted as an expression of an outdated mindset, when analogue methods are directly migrated to digital equivalents, and conceptually misaligned with what the digital methods provide. Data are "dumbed-down" and complexity is reduced to what archaeologists traditionally deal with. For instance, a highly detailed, photorealistic 3D documentation may be adopted only as the means by which an orthophoto is generated. Consequently, the three-dimensional information is discarded and the documentation is used only as a digital equivalent to a traditional hand drawing. Furthermore, archaeology works at many levels of resolution from intra-site to inter-site, and a consistent level of documentation detail has proven difficult to produce, which often relates to the scale and scope of the prevalent research questions (Wheatley and Gillings 2002). Despite the early application of GIS, archaeologists have failed to transform GIS from a simple tool into a proper data management or research instrument, with methodological and theoretical implications (Merlo 2016).

This research is therefore concentrated on the role of three-dimensional representations in digital archaeology, including the tools needed to harness their full potential, and the data models required to better integrate and disseminate joined spatial and non-spatial data. From the point of view of archaeological fieldwork, the research describes an effort to integrate complex spatial data, primarily derived from image-based 3D documentation, and seeks to develop a conceptual structure which encourages and enables the use of 3D as a tool in the archaeological process. This requires a framework or infrastructure which facilitates combining data in an open data model and also provides interoperability and re-usability of the bulk documentation data. The framework is tested in practice, implemented and developed around specific Danish research excavations, primarily Jelling (Holst et al. 2013) and Alken Enge (Holst et al. in press), while its scalability is tested against national datasets of excavation data (MUD 2014).

1.1 Research motivation

The inspiration for the research into complex spatial data and appropriate data models derives from my own experiences with digital documentation at Danish research excavations. The special joint position between the University of York and Aarhus University provided by this PhD project offered opportunities to compare and synthesise experiences from both institutions regarding excavation methodology, digital documentation and practices of archaeological data archiving.

The overall premise for the research is the significant lack of integration when it comes to data produced by archaeological excavation documentation. This calls for a data model, which more coherently integrates all the types of digital data that an archaeological excavation may produce. Specifically, most excavation drawings are detached from the written classification. This is true for analogue data as well as digital spatial data, and becomes increasingly evident when we talk about drawings of vertical sections and other complex visual representations used for excavation documentation, which do not fit into the top-down projection scheme of mainstream GIS. The outcome is a parallel series of related and derived data, which only to some extent are properly referenced.

It is therefore of growing concern that 3D documentation techniques are increasingly accepted and applied, despite serious limitations to the technical frameworks normally used for spatial data, such as GIS or CAD. These systems were never originally intended to include nor visualise such 3D data. The new data types generated do not integrate easily with our traditional documentation workflow either. Despite the revolution of spatial field recording attributed the introduction of high precision GNSS/GPS for drawing digitally (and fast), the most common GIS solutions do not offer the necessary tools for managing the full complexity of archaeological recording. Concurrently, an increasing amount of "born digital" data is generated, which does not produce the archival paper trail we are used to dealing with. While a digital excavation plan may be easily printed on to paper, rectified documentation photos, photogrammetry, Structure From Motion and laser scanning challenge how we manage, integrate, analyse, disseminate and archive data.

Figure 1.1: The author and colleagues from Aarhus University and Skanderborg Museum while excavating at Alken Enge. All stratigraphic units are recorded using imaged-based 3D documentation/Structure from Motion techniques. Photo: Ejvind Hertz.

The lack of spatial data-integration is not only related to limitations in our tools and the legacy of historical excavation traditions, but also to the continuous method development, which is particularly closely linked to the technological advances, and how these are adopted and adapted in archaeological practice.

Of particular interest is the potential of Structure from Motion for creating photo-realistic 3D models and similar techniques for photogrammetric field recording, as they may constitute a new methodological framework, bridging a methodological gap between different field archaeological traditions. Excavation techniques vary significantly according to geography, the political landscape, local traditions and the nature of the archaeological sites themselves, although most agree that common methods are the standards by which it is possible to truly compare and interpret archaeological data at the larger scale. Yet technology plays an increasing role, as it offers faster and thus cheaper ways of documenting archaeology in a world of contract and rescue archaeology, with potentially adverse effects (Kristiansen 2009). This may, however, be about to change as the interaction between new technology and different prevalent archaeological excavation traditions evolves. An area where this development would potentially have profound impact is where the single-context ideal (Harris 1979) is contrasted by vertical sectioning of archaeological features (Carver 2009; Carver et al. 2015) as observed in the diverging excavation methods of Danish and British archaeology. In this case, 3D documentation may constitute a middle ground of recording principles, where single context planning and strict stratigraphic excavations meet the arbitrary, pragmatic geometric sectioning of features.

In addition to the philosophical implications of a new paradigm of 3D photo-realistic documentation, this “new-objectivity” has arguably profound methodological impact on several aspects of field recording. It offers a new conceptual interface or structure of visual representation, which forces us to construe how an object in a 3D representation relates to a feature in the reality of the past.

The new tools and methods affect the interpretation flow and how we perceive and identify the relationship between objects, and they redefine how we collaborate with other researchers. They also mean having to deal with concepts of certainty and authenticity, which may be used not only to describe the documentation quality but also to discern between observation and interpretation - documentation and model. Just like the general use of models to form hypotheses, it is possible to use 3D models as spatial hypotheses in an ongoing excavation. This allows us to visually realise or spatially conceptualise our hypothesis as a virtual reconstruction and to combine it with our observational data. Instead of using traditional drawing conventions to delineate the archaeological interpretations, we are actually able to interpret and visualise through 3D modelling of a spatial hypothesis, rather than working with lines and sketches. This in turn requires strict guidelines, and regard for the separation of observation and spatial hypothesis, and insurance that the one is not mistaken for the other.

At present, there is much focus on making our 3D documentation as photo-realistic or reality-proximate as possible, to even the smallest details. I argue that this may not necessarily be the most purposeful ideal for our documentation. Instead we may consider redefining the documentation ideal by experimenting with the use of volume pixels or voxels to enhance the information retained in 3D documentation. Voxels are interesting from an archaeological point of view, because they require working with volumes rather than surfaces, which corresponds more closely with our traditional archaeological construct of contexts or layers.

One of the main driving-forces behind digital archaeology was the advantage of separating data into quantitative elements; discrete chunks, which can be easily and efficiently organised and analysed. In fact, I propose that the major challenge we face in the integration of archaeological documentation data, is exactly where we choose to not separate data types into their basic constituents: for example all photos, drawings and of course the digital spatial data, which are handled internally in GIS or CAD, and not described explicitly. Paradoxically, what 3D documentation is adding are new, often proprietary data formats, which are also difficult to split up into their constituents and integrate. Instead we risk ending up with static 3D representations of our documentation with limited analysis capabilities, not unlike what an analogue hand drawing represents in the first place.

1.2 Research objectives

A series of research questions act as guides for the study, which may broadly be divided into four themes:

- Evolving ideals of spatial recording as influenced by technological advances. Does the introduction of new complex data types in archaeological excavation documentation necessitate a re-evaluation of the end-goal of the archaeological excavation itself and the way archaeologists perceive data? What is the aim or end-goal of the documentation? How does this link to archaeological practice?

- 3D models as observation and interpretation.
  New types of data provide an unprecedented level of precision and represent a new conceptual layer of observation. How does this change the way we think, and what new methodological approaches can we apply? Is archaeology at a threshold, at risk of abandoning the traditional interpretative and reflexive archaeology, for the sake of documentation that appears to correspond more closely to the observed "truth"? If so, how do we apply this to the current workflow of archaeological documentation without losing the dimension of interpretation and scientific research? Do we just take complex data as fact without concern for the sources of error and validity, and where does archaeological interpretation fit in a new approach? How does it function as a tool for hypothesis validation?

- Analytical potential of 3D documentation.
  What are the analytical possibilities and potential of 3D documentation? What is needed to fully exploit this potential? Are there ways of employing machine learning, pattern recognition or semi-automated classifications of 3D models and how do we embed archaeological knowledge and interpretation into the 3D models?

- Data structure and conceptualised spatial data for management and interoperability.
  How do we ensure a data structure that is simple enough to be practical for field work, yet complex enough to include information about data itself: observation, interpretation, validity and authenticity, processing, analysis and archiving? What is required to ensure the availability of complex archaeological data for analysis? How do researchers best exploit the information embedded in the new data types in regards of quantitative methods?

In order to inform the broader research questions, the specific objectives of this research are:

1. To review the role of 3D image-based documentation, and how a re-conceptualisation of the archaeological workflow may aid in the management and analysis of complex spatio-temporal data.

2. To explore and develop tools dedicated at enhancing the analytical potential of 3D recording and visualisation.

3. To define a data model and data structure which is dynamic and flexible, yet simple and transparent, and which integrates all types of archaeological data.

4. To implement the data structure as a framework, showcasing data management capabilities, analytical queries, various spatial and visual representations and data interoperability.

1.3 Scope of research

Archaeological excavation theory has received much attention since the late 1990s and early 2000. Most of the discussion relate to the post-processual claims of Ian Hodder, and are primarily concerned with the epistemology of archaeological research; in particular the dichotomies of interpretative vs. scientific or objective vs. subjective (Madsen 1995; Hodder 1997, 1999; Lucas 2001). Yet with an exception of Roskams (2001:267) and Hodder (1999), very few publications consider the practical application of information technology from the point of view of actual field manuals. Instead, the focus tends to remain centred on the effects of new spatial technology on archaeological practice from a knowledge-creation standpoint. Even though countless articles focus on technical aspects of archaeological data management and spatial analysis, this is often aimed at specialists and not targeted at the broader archaeological community and, perhaps least of all, the actual people doing fieldwork, who experience the innovations first hand in everyday excavation practice. Research is focused on digital methods in archaeology, rather than digital methodology, and rarely in the context of an entire excavation workflow and the important role played by spatial conceptualisations. Yet recent years have witnessed an increased focus on the management of spatial data in combination with fieldwork practices (De Reu et al. 2014; Berggren et al. 2015; Forte et al. 2015; Dell'Unto 2016; Dell'Unto et al. 2017).

The subject of digital applications in archaeology and cultural heritage is extremely wide, and the research has no intention to solve all aspects of the matter. As a result, the emphasis is on spatial data related to archaeological excavations only, and does not consider artefact analyses or spatial analyses in the broader sense. Concurrently, continuing digital advances and the availability of new, better and faster technology also means that what is the "state-of-the-art" of today is the "old-fashioned" of tomorrow. Evolving technology is both the target and the premise of the research, where continuous advancements have led to a situation where the theoretical framework of the archaeological documentation process struggles to keep up. Different applied techniques for creating three-dimensional representations of archaeological excavations result in new types of data, emphasising an urgent need to start treating archaeological information as both dynamic and multidimensional - that is, including all three spatial dimensions and time. This will allow better modelling of reality and visual representations of the phenomena which archaeology tries to describe.

While the research does address theoretical concepts of archaeological interpretation and objectivity, and how new technology such as 3D recording affects the epistemology of field recording, the main scope of this research is method-based. The theoretical perspectives serve to assess the scientific value and challenges of dealing with new data types, new concepts and new documentation end-goals, but the research does not actively seek out a philosophical debate concerning the implications of new technology at "the trowel's edge". Instead, the methodological perspective focuses on developing tools for documentation and management of complex spatial data and the design of a data model capable of integrating complex spatial data into the archaeological process and research. This is emphasised through the development of the Archaeo Framework, which constitutes an important objective and contribution of this research.

This research does not aim to be a new field manual of digital documentation tools, rather it seeks to bring tools of spatial data management to the field archaeologist, while facilitating excavation data to become findable, accessible, interoperable and re-usable.

1.4 Methodology

Based on the research objectives, three levels of research have been undertaken, comprising conceptual, operational and implementation levels. From the perspective of method-development and practical implementation, the study progressed as a dialectic process between actively developing a database, infrastructure and user-interface while engaging with related topics. Throughout the process, the practical implementation and public presentations provided continuous feedback from users, colleagues and peers. This resulted in an iterative process, whereby the formulation of ideas led to practical operations, implementations and evaluations.

1.4.1 Conceptual level

The initial phases of the project examined the conceptualisations of spatial data in archaeology, and how they are handled, both historically, from the perspective of varying excavation traditions, and as a consequence of emerging technologies. This entailed focusing on the conceptual abstractions required by new forms of documentation, and how concepts like authenticity play a role in negotiating between observation and interpretation - between documentation and reconstruction. It also meant discussing the ideal of photo-realistic 3D documentation versus conceptualised representations based, for instance, on drawing conventions, semantics, symbols or alternative generalisation and the visualisation of spatial data.

From the point of view of excavation methodology, the long chains of derived data produced by digital recording and processing become increasingly influential when assessing the validity of archaeological observations and interpretations. For this purpose this study explored an event-based approach for conceptualising how digital spatial data are created, derived and evolve throughout the documentation- and post-excavation process. This effectively meant building a conceptualisation around excavation recording procedures and seeing them through to the data model implementation itself.

1.4.2 Operational level

The operational phase was inevitably a mix of conceptualisation and implementation, but further explores the potential of 3D as an analytical and information-carrying tool. It addressed the concern that it is currently very difficult to embed any elaborate information in a 3D model, unlike in traditional GIS vector layers. It therefore became a priority to develop tools which allow enhancement of the semantic value of 3D models, and to consider how machine learning and automated processes may aid in the archaeological process. These do not replace the archaeologist, but aid in the classification of 3D data, which is a laborious process to do manually. This and the implementation phase involved substantial amounts of coding in Python, PHP and JavaScript to develop and explore.

Finally, the data structure for managing archaeological spatial data was evaluated against existing conceptual reference models and ontologies, while contemporary research on the semantic web, online vocabularies and thesauri was explored.

1.4.3 Implementation level

The final phase included the data model design, data structure development and led to several iterations of data models, data management systems and front-end implementations. This phase was also used to explore the case datasets of Jelling and Alken Enge.

1.5 About this dissertation

This work finalises a 5+3 PhD project within the joint doctoral programme in Digital Heritage established in collaboration between the History, Archaeology and Classical Studies Graduate School, in the Faculty of Arts, Aarhus University and the Department of Archaeology, University of York. The project was originally entitled: "An Archaeological Data Model for Complex Spatial Data" and was initiated January 1st 2015 and finalised March 12th 2018. The main supervisor of the project for the initial 2 years was Professor Mads Kähler Holst, Department of Archaeology and Heritage Studies, Aarhus University now museum director at Moesgaard Museum. He was replaced by Associate Professor Jens-Bjørn Riis Andresen, Department of Archaeology and Heritage Studies, Aarhus University. Co-supervisor has throughout the project been Professor Julian D. Richards, Department of Archaeology, University of York.

1.5.1 Structure of the dissertation and associated rich media

The PhD dissertation is composed of four individual articles, which constitute individual chapters (2-5). Each chapter covers a theme within the overall topic of integrating spatial data in archaeology, supplemented by this introductory chapter, a synthesis (chapter 6) and a concluding chapter, including summaries in English and Danish. The research into data integration and spatial visualisation is simultaneously published online as proof of concept through the development and implementation of the Archaeo Framework located at `www.archaeo.dk`.

Each article is written with the chapter progression of the dissertation in mind, but is also intended for separate journal publication, and may thus be read individually or as part of the whole. Chapters 2, 3 and 4 are based on papers presented at various archaeological conferences, and were written in the context of the individual conference session themes, and in the style of the subsequent journal publication. Chapter 5 is a finished manuscript ready for submission.

2. *Where are we? Reviewing the Integration of Complex Spatial Data in Current Field Archaeology.*
   The article has been reviewed, accepted and published in Internet Archaeology.

3. *Evaluating Authenticity: Authenticity of 3D Models in Archaeological Field Documentation.*
   The articled has been reviewed, accepted and is in-press as chapter 5 in "Authenticity and Cultural Heritage in the Age of 3D Digital Reproductions" (Di Giuseppantonio Di Franco et al. 2018)

4. *Semantically enhanced 3D: A web-based platform for spatial integration of excavation documentation at Alken Enge, Denmark.*
   The article has been reviewed, accepted and is in-presss for publishing in a special issue of Journal of Field Archaeology titled "Web-based Infrastructure as a Collaborative Framework across Archaeological Fieldwork, Lab Work, and Analysis", Galeazzi, F. and Richards-Risetto, H. (eds.)

5. *Beyond 3D: Extending Dimensions of Image-based Documentation in Archaeology.*
   The manuscript is ready for submission. The article is co-authored with David Stott, Aarhus University.

The chosen format clearly has a number of advantages and disadvantages. Although the advantages outweigh the disadvantages, by providing a format in which it is possible to present a number of distinctly different papers, it can be difficult to obtain the same coherency compared to a monograph. It is, nonetheless, expected that the additional chapters offer a satisfactory framework to provide a coherent piece of work. In order to further this, the articles have been formatted according to a standard layout, specifically for this dissertation. It should be stressed that the contents of the different chapters correspond fully to that of the original papers, except for minor revisions to references and bibliographies. Chapters 6 and 7 seek to synthesise the main arguments of the preceding chapters, while introducing the data model design considerations and implementation.

In line with the theme of complex spatial data, the use of rich media for illustrations and figures has been a priority throughout the dissertation. Two journals have additionally accepted embedded videos for online publication. Obviously this does not correlate with printed copies of this dissertation, nor does the Portable Document Format (pdf) currently guarantee support of embedded rich media on all platforms, mainly due to proprietary dependencies.

As a compromise, all illustrations which refer to a video or 3D animation have been watermarked in the top of the image, clearly stating that it is a video. The actual videos have been uploaded separately to `https://vimeo.com/album/5006673` (password: phd), and each video-illustration in the pdf is clickable with links leading directly to the individual video for web-browser viewing. Furthermore, all URLs for the videos are in the captions and List of Figures.

It should be stressed, that the full impression of the dissertation requires internet access to properly view the associated illustrations and explore the Archaeo Framework.

1.5.2 Chapter 2

The article presented in chapter 2 is intended as an introduction to the overarching research questions and the methodological and historical background. It offers some rudimentary impressions of differing excavation and recording traditions in Britain and Denmark, related to the joint nature of the PhD project. Furthermore it provides a critical assessment of the use of Geographic Information Systems in archaeology, and the trending negotiations between state-of-the-art technology and archaeological practice. *"Where are we? Reviewing the Integration of Complex Spatial Data in Current Field Archaeology"* (Jensen 2017) was published in the special issue of the journal*Internet Archaeology* entitled Digital Creativity (Beale and Reilly 2017). To cite the editors:

> "The application of CAD and GIS for the digitisation and management of spatial data collected in the field are two cases in point. Peter Jensen reminds us that CAD was a technology originally developed as an architectural design tool but was press-ganged into the uncomfortable service of archaeological mapping. GIS too, with vast spatial analytical capabilities and, albeit limited, embedded databases, was ultimately inherently constraining for the simple reason that 3D archaeological data collected in the field are straight-jacketed into 2D abstractions (i.e. 'layers'). Ultimately the introduction of both CAD and GIS technologies seems, so far, to have contributed significantly to the detrimental effect of creating stand-alone silos of spatial data that are rarely fully integrated with non-spatial, textual data, or what we might more broadly consider as the archaeological documentation. As such, they are open to the charge of having stifled the development of digital standards of recording by perpetuating outmoded analogue recording conventions from a previous century. Jensen attempts to break free of these anachronistic shackles by exploring and testing born-digital 3D recording technologies such as SFM and Range Imaging, GPS, and laser scanning in current practice. He deliberately adopts a open-minded approach to begin the process of conceptualising new types of data and data representation in archaeological documentation, accepting that

they probably will not fit into our usual concepts of interpretation, and in all likelihood will require changes in our methodologies and workflows, potentially signalling a paradigm shift, redefining explicitly what we actually want to do with our spatial data. It becomes important to recognise the conversational nature of this exchange. Jensen's self-consciously explorative and negotiated approach epitomises a healthy discursive relationship between archaeologists, digital technology and praxis. Far from being passive consumers of technology, archaeologists need to be involved in a constant negotiation with technology, informed by cultures of research and practice."(Beale and Reilly 2017).

1.5.3 Chapter 3

The thesis revolves around the overarching goal of developing an archaeological data model for complex spatial data. By its broadest definition, a model is used as a simplified representation of some sort of reality, and the thesis not only deals with data models, but equally important concepts of spatial models and models for building and testing research hypotheses. The article in chapter 3 seeks to advance the conceptual framework of 3D models within archaeological excavation recording. 3D documentation advocates for a new workflow with a more 3-dimensional reasoning, allowing for the utilisation of 3D as a tool for continuous progress planning and evaluation of an excavation and its results. Just like the general use of models to form hypotheses, it is possible to use 3D models as spatial hypotheses on an ongoing excavation. This allows us to visually realise or spatially conceptualise our hypothesis as a virtual reconstruction and to combine it with our observational data. Chapter 3 employs the concept of authenticity to assess the quality and use of photo-realistic 3D models – not as reconstructions but as representations of field observations. These are contrasted by 3D models or reconstructions, which are based on hypotheses and often used for dissemination. Combining such spatial models will help negotiate and promote the dialectics concerning archaeological field recording data, and whether we apply "top-down" or "bottom-up" approaches, if even such a duality exists. This has the potential of making the decision process of an archaeological excavation far more transparent, and aid in illustrating the premises for the archaeological process. For instance will visualising the initial excavation hypothesis as a 3D model provide an account of the initial decisions and conditions which define the excavation process. The chapter showcases the question of authenticity and highlights the challenges of uncertainty when navigating the zone between research hypothesis and public dissemination. *"Evaluating Authenticity: Authenticity of 3D Models in Archaeological Field Documentation"* (Jensen 2018) was published in the book titled *"Authenticity and Cultural Heritage in the Age of 3D Digital Reproductions"* (Di Giuseppantonio Di Franco et al. 2018). The article was written in the context of a paper-presentation at EAA Glasgow September 2-5 2015, which discussed the value of 3D digital and physical replicas of ancient material culture, how these digital and virtual reproductions should be considered and whether they are authentic representations of our cultural heritage or just virtual and physical "fakes". A special focus was how 3D digital and printed replicas challenge and redefine the notion of authenticity in archaeology and heritage studies.

1.5.4 Chapter 4

The article in chapter 4 further addresses the problems inherent to 3D documentation: its inability to convey archaeological interpretations. By example of the excavations at Alken Enge, Denmark, this article explores how a web-based 3D platform is able to facilitate the collaborative exchange of 3D excavation content and how the integration of spatial and attribute data into one common event-based data model may be advantageous. This includes enhancing the semantic value of field-recorded 3D models by segmenting the geometry using various techniques. *"Semantically enhanced 3D: A web-based platform for spatial integration of excavation documentation at Alken Enge, Denmark"* has been accepted for publication in the Journal of Field Archaeology special issue titled: *"Web-based Infrastructure as a Collaborative Framework across Archaeological Fieldwork, Lab Work, and Analysis"*, Galeazzi, F. and Richards-Risetto, H.(eds.); and represents a re-write of a paper presented at the Computer Applications and Quantitative Methods in Archaeology conference, March 2017 in Atlanta. Furthermore, this chapter represents an offshoot of activities associated with Archaeology Data Service in York and Fabrizio Galeazzi, including presentations at CAA-UK 2016, CAA-DK 2016 and acting as presenter and session chair on collaborative frameworks at the CHNT 2016 Conference in Vienna (Galeazzi and Jensen 2016).

1.5.5 Chapter 5

The article in chapter 5 further explores the technologies outlined in chapters 2 and 4. In particular it focuses on evaluating analytical capabilities and alternative visualisation ideals for 3D data. The chapter presents a simple case study, demonstrating the pipeline from archaeological feature, through image-based documentation and processing to volumetric visual representation, while exploring the potential of machine learning to aid in feature recognition and classification. *"Beyond 3D: Extending Dimensions of Image-based Documentation in Archaeology"* is co-authored with Dr. David Stott, Aarhus University and the manuscript is ready for submission to a peer-reviewed scientific journal.

1.5.6 Chapter 6

Chapter 6 is the thesis synopsis and focuses specifically on data models while synthesizing perspectives from chapter 2-5 on digital excavation methodology and the challenges of integrating complex spatial data in archaeological field recording. The chapter discusses archaeological data models in general, conceptual reference models and introduces the specific Danish institutional context and the multi-stakeholder requirements for the proof of concept developed for this research project: the development and implementation of a flexible data model for integrating complex spatial data in an open and interoperable online infrastructure, the Archaeo Framework. The Archaeo framework was developed as an online and collaborative platform with a highly customisable and flexible ontology for research excavations. It was developed from onsite and practice based, explorative research and includes tools for harvesting existing data into one common data model for all textual and spatial data. The framework is showcased through an introduction to the basic functionalities of the user-interface, including the 2D and 3D online viewers and the comprehensive textual classification system. Furthermore, several technical considerations during development and implementation are discussed.

1.5.7 Chapter 7

Finally, chapter 7 provides some concluding remarks and English and Danish summaries.

1.6 Bibliography

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2

Where are we? Reviewing the Integration of Complex Spatial Data in Current Field Archaeology

Jensen, P. (2017)
Internet Archaeology 44

Abstract: This article examines the background and current challenges of integrating spatial data in field archaeology, particularly in the light of ongoing technological advances. This is done through a brief comparative overview of the development of field recording principles in the UK and Denmark. Archaeology in the two countries historically represents two different standpoints of methodological traditions and corresponding ideals of documentation. The question is, if technological developments – and not least the limitations of the applied digital frameworks – have been an important defining factor and continue to affect the reconditions of the methodological development when it comes to spatial data recording and the advent of more complex spatial data.

This article demonstrates that 3D documentation techniques are indeed increasingly accepted and applied despite the limitations of technical frameworks such as GIS or CAD. Even more interesting is the potential of Structure from Motion and similar techniques for archaeological field recording as it may constitute a new methodological framework, bridging the gap between different field archaeological traditions; a middle ground of documentation principles, where single context planning and strict stratigraphical approaches meet the arbitrary, pragmatic geometric sectioning of features.

Although different methodological approaches clearly relate to an ideal with consequences for our archaeological praxis, excavation and documentation methodologies are not necessarily restricted or determined by the available technology. Modern archaeology tends to be sufficiently open-minded and in support of continued experimentation, which is required to manage new and different methods of data acquisition and spatial documentation and representation.

2.1 Introduction

Spatial data lie at the heart of archaeological documentation. In fact, one could argue that no single piece of evidence collected at any step of the documentation process exists without some degree of embedded spatial information. The most obvious is of course the distribution of finds and features. However, any drawing we make and every photo we take - even all our archaeological interpretations and classifications -relate to a spatial record of what took place where and when, both in terms of the historical past as well as the archaeological present.

The attention to spatial recording is indeed one of the technical preconditions to the interdisciplinary nature of archaeology. Early excavations were often carried out using the skills and knowledge of not only archaeologists but in particular architects, land surveyors, and cartographers (Piggott 1965). Eventually, post-excavation quantitative methods and analyses as well as the use of predictive modelling in cultural heritage management called for skilled mathematicians and statisticians. Technological developments have revolutionised the availability and applicability of an entire array of scientific investigations, from remote sensing and geophysical surveys to isotopic and morphological dating and analyses (Kristiansen 2014). These all rely on sampling strategies where spatial information accounts for the critical assessment of context, formation processes, and the risk of contamination.

Recent decades have witnessed a series of distinct tendencies in the development of spatial recording within field archaeology, not least related to the migration of analogue methodologies into digital equivalents, where the use of CAD and GIS are the most prominent examples. These tendencies are arguably at the core of the challenges modern archaeology faces today when it comes to the integration of spatial data in the documentation process. They are in part the result of an increasing willingness and eagerness to test out and apply new technologies. The downside is that new technologies are very rarely developed specifically with archaeology in mind (Richards 1998, 331), and applications and adaptations fail to recognise potential negative consequences of this fact.

We have begun to witness the impact of new tools for creating accurate 3D content, specifically photogrammetry and range imaging techniques such as Structure from Motion (SFM), which is something archaeology has aspired to ever since computers were introduced to archaeology (McCoy and Ladefoged 2009). Most likely we have only experienced the beginning, and the technology responsible is developing fast. Just as archaeological documentation frameworks were starting to catch up with solutions for managing the new digital methodologies of spatial data, the concept of spatial recording has 'gone 3D' and expanded into new visual and conceptual representations.

It is the aim of this article to examine the background and current challenges of integrating spatial data in field archaeology in the light of ongoing technological advances. This is in part done through a comparative overview of the development of field recording principles in the UK and Denmark. Archaeology in the two countries represents different standpoints of methodological traditions. Do these differences affect the preconditions of technological development or vice versa when it comes to spatial data recording and the advent of more complex spatial data?

2.2 Field Recording in the United Kingdom and Denmark

Although historically developed from very similar backgrounds, current archaeological excavation methods in the UK and Denmark show characteristic differences. These differences relate not only to field recording, but to the ideal of archaeological documentation itself. Arguably, each side has limited understanding of the other methodology, but more interesting is how the differing excavation methods have adapted to and implemented digital documentation technologies.

Going back to the very beginning of field archaeology, the 19th century represented a starting point, characterised by an emphasis on acquiring and collecting artefacts and finds, arguably often achieved through an unsystematic and cursory approach. By the late 19th century, more consistent methods slowly emerged, driving field archaeology towards a more empirical-inductive methodology and focusing on the balance of archaeology between observation and interpretation (Marsden 1983; Darvill 2015). The introduction of archaeological positivism, in its quantification of all observed facts, meant a need for structuring investigation methods and recording systems, eventually leading to a situation where spatial recording was considered a basic, fundamental observation from which all objects derive meaning. The context of the artefact became important.

In the UK, one of the first to realise the importance of the archaeological spatial context was ethnologist and archaeologist Augustus Pitt Rivers (1827-1900), who in his efforts to explore social evolution introduced methods for the documentation of long-term development and activity sequences (Bowden 1991). Effectively, this meant the introduction of plans and section drawings, allowing for the accurate recording of spatial distribution of features and artefacts. Contributions by Flinders Petrie (1853-1942) regarding relative chronologies and Mortimer Wheeler (1890-1976) followed. Wheeler is perhaps most famous for the Wheeler Box-Grid trench system, where an excavation is divided into squares separated by baulks and sections, but he was also one of the first to systematically record stratigraphy in the UK as well as overseas in Egypt, India and Pakistan (Lucas 2001). The introduction of these tools meant that the required elements to do simple spatial recording were present, and the same basic principles of spatial and stratigraphical recording is still widely in use today.

Within the same timeframe, continental European methods saw a similar development. Archaeology in Scandinavia in the early years also focused almost exclusively on the artefact. However, emphasis on the development of typologies, starting with Christian Jügensen Thomsen's (1788-1865) division of prehistory into Stone, Bronze and Iron Ages and Jens Jacob Asmussen Worsaae's (1821-1885) observations regarding stratigraphy may be some of the most well-known Danish contributions (Gräslund 1987). The early to mid-20th century also witnessed developments in field methodology. The aftermath of the Second World War meant opportunities to examine many of the medieval market towns all over Northern Europe. Such urban excavations adopted the UK system of stratigraphical recording, owing to their often very deep and complex sequencing of building traces.

During the 1930s-1950s Gudmund Hatt (1884-1960) and Carl Johan Becker (1915-2001) were among the first to use large-scale open-area excavations to aid in the identification of prehistoric building structures, focusing on the exposure of large areas, where little more than postholes were preserved – which, unfortunately, is the case for most excavations in Scandinavia (Hatt 1928; 1938; Becker 1948; Larsson 2015). The abundance of settlements, especially of the Iron Age, exhibiting only modest stratigraphical information subsequently led to the adoption of the so-called German approach, where archaeological features are spatially documented through horizontal and vertical sections or 'schnitt'; a method that today is by far the most common approach to rural excavation in Denmark and Southern Scandinavia. In the same period, Harald Andersen (1917-2005) and Mogens Ørsnes (1925-1994) in particular developed methodologies related to the excavation of the stratified, vast wetland Iron Age weapon deposits, but with much greater emphasis on structures of features rather than 'just' stratigraphy of contexts (Andersen 1956; Ørsnes 1963; Becker 1966). Ørsnes later became editor and contributor to the Danish Field Archaeology Manual (Schou Jørgensen et al. 1980).

The 'continental methods' for open-area excavations were exported back to the UK, and widely applied throughout the 20th century, for example by Hurst (1927-2003) at the excavations of the medieval village of Wharram Percy between 1950 and 1990 (Beresford and Hurst 1990), and the deeply stratified sites of Winchester by Biddle and Wroxeter by Barker (Barker 1980; Biddle 1990; Barker et al. 1997; Collis 2011; Everill and White 2011). The same methods are recurring themes throughout the general methodological development in the UK, as depicted by authors such as Richard Atkinson (1946), John Coles (1972), Philip Barker (1977), Ian Hodder (1999), Steve Roskams (2001) and Martin Carver (2009). Excavations in the UK have, however, predominantly retained focus on the development of stratigraphical and single context recording, i.e. excavation by means of removing and correlating individual layers or contexts (Darvill 2015). Single context recording was developed by Ed Harris (1979; Harris et al. 1993) and widely adapted and developed in the UK during the 1970s and 1980s, specifically for deeply stratified urban archaeology. It was primarily seen as an attempt at formalising field recording in a universal structure of contexts or strata, which is descriptive rather than interpretative. The interpretation takes place post-excavation, which in later years interestingly is opposed by attempts at enabling a more reflexive approach to field archaeology, as illustrated by Hodder's interpretation at 'the trowel's edge' (Hodder 1997; 1999; Berggren et al. 2015).

For the sake of this article, methodological discussions and justifications for either approach is not the primary focus, but serve to illustrate the existence of two methodologies branching into several ways of doing archaeology. It is not a matter of single context recording vs arbitrary sectioning and slicing, or United Kingdom vs Denmark; all over the world methods vary according to geography, research questions and perhaps not least the political and cultural context in which the archaeology is exercised (Felding and Stott 2013; Carver et al. 2015; Madsen 1995). As a consequence, we generally observe a change from the very rigorous approaches to the more pragmatic hybrids. It is, however, very important to realise how the two objectives or ideals of documentation relate to different practices of epistemological traditions, and in turn how these relate to spatial recording in an evolving digital world.

2.3 Documentation: Spatial Recording in an Evolving Digital World

Regardless of the chosen excavation methodology, just a few decades ago most archaeological excavations were characterised by a comparable set of tools relating to the activities we usually expect from archaeology: excavation, documentation and interpretation. At the heart of the documentation was - and still is - the spatial recording of contexts, features and distribution of finds. Spatial observations and interpretations are transferred to paper in the form of hand-drawn sketches of identified features, complemented by sheets or lists of contexts, classifications and descriptions of relationships between various entities. All are fairly easily managed by analogue tools - pen and paper.

Since then, new tools have slowly found their way into archaeology, a development that may be best illustrated through the proceedings of the annual conference of Computer Applications and Quantitative Methods in Archaeology from 1992 until the present day (CAA). We clearly see a digital development in areas of data management and quantitative analysis, but also in evidence is an increased focus on managing spatial field data in Geographic Information Systems (GIS) or Computer-Aided Design systems (CAD). This progress marks the starting point of a still ongoing digital revolution of spatial recording in archaeological fieldwork, following the general trends of technological development in a world of faster computers, global satellite navigation systems and digital equipment for remote sensing and surveying. At the same time, archaeologists must deal with dichotomies of data which are either 'born digital' or derived through some sort of digitisation process.

2.3.1 Geographic information or computer-aided visualisation?

Not only did field archaeology in the UK and Denmark branch out into two separate methodological approaches but the digital adaptations of spatial recording and management were from the very beginning also divided into two separate technologies: CAD and GIS.

Historically, Computer-Aided Design solutions had strong ties to archaeological fieldwork, and often to people or specialists with a background within cartography or surveying (Holst 2005). CAD was originally, as the name implies, developed as a designing tool, allowing for very precise and fast prototyping of machine parts and easy scalability between vector drawing on a computer and a real-world object. Dealing with objects on a designer-level, and even allowing for the drawing of three-dimensional vector lines, also meant that CAD became an essential tool for architects. It was, however, never meant as a mapping tool, and lacked the support of geographic coordinate systems, limiting its usage as an intra-site tool for archaeology. Relatively early applications including graphics databases were seen in the UK in systems like PLANDATA (Alvey and Moffett 1986), AEGIS, as used by the Scottish Urban Archaeological Trust (Rains 1989), and Hindsight (Alvey 1993), which extended the capabilities of AutoCAD to produce composite plans and three-dimensional models from single-context plan elements.

Geographic Information Systems, on the other hand, were created as tools for more than simply drawing vector lines and, as the name implies, were 'born' geographically aware, with the ability to present spatial information by applying a map projection. Furthermore, unlike CAD, GIS included support for topology and thereby tools for calculation and analysis of spatial functions, which were very promising for archaeological investigations of spatial distributions and topographical analysis (Conolly and Lake 2006). GIS was primarily adapted through Desktop Mapping solutions, which provided the integration of semantic content or 'information' and allowed for the association with a geographic vector representation of an object or feature. The support for georeferencing rasters also meant that traditional hand-drawn excavation plans could be scanned and managed by the GIS systems, allowing for stacking or layering drawings – providing coherency and explorative capabilities to vast amounts of spatial data, with little other effort than scanning. Combined with vectorisation tools, GIS would appear superior to CAD, were it not for its basic premise; that everything is represented as a geographic projection onto a surface, meaning that three-dimensional data had to be contained within a two-dimensional visualisation.

The motivation for choosing either technology not only relates to the traditions and professional background of the people involved, but also to an issue of availability and affordability of the software, which early on was limited to often expensive proprietary solutions (Holst 2005). Interestingly, there are also clues to the rationale behind the choice of either technology for representing spatial

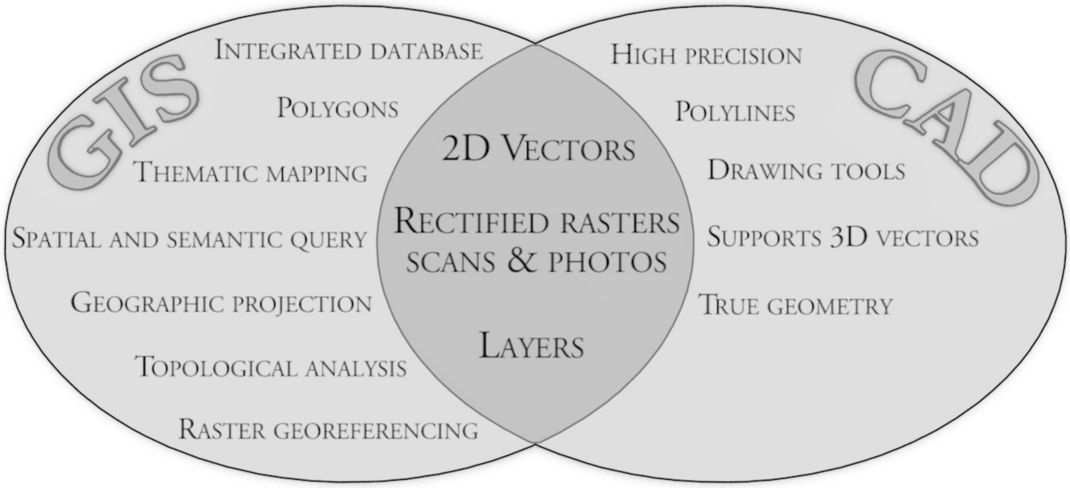

Figure 2.1: GIS and CAD. The 'traditional' features of Geographic Information System and Computer-Aided Design, converging on what has become an ideal for archaeological documentation.

recording if we examine the ideal of different archaeological methodologies or traditions. Specifically the choice between GIS or CAD very well illustrates how the choice of technology is tied into tradition-related preconditions; the ideal, goal or end-product of our documentation.

Common to both technologies, as they are implemented in archaeology, is the goal or de facto standard of representing archaeological features, contexts and finds as vector geometries; points, lines and polygons (see Figure 1). It is, however, important to recognise that, apart from perhaps 3D vectors, GIS and CAD have been applied as equivalent to our analogue procedures, hand drawings, and as the development of both archaeological methodologies and spatial technologies took place in the same time span, they have inevitably had a profound impact on each other. Large-scale single context planning benefits immensely from proper computer power and digital tools to handle what otherwise would be extremely fragmented recording. On the other hand, the methodology of excavation by stacking two-dimensional layers is directly comparable to the representation that was possible - or limited - by standard GIS and CAD.

Due to its embedded database capabilities, GIS would appear as the best choice, seen from the perspective of enhancing our traditional drawing with semantic information, and it is perhaps the most critical limitation to CAD, which had to rely on external database solutions. Unfortunately, the GIS concept in its most basic sense is limited to storing associated data in a single table, corresponding to spatial objects in a one-to-one relationship. Any archaeological registration system will show that this is not the real-world situation! The eventual outcome is the splitting up of spatial and textual documentation, potentially rendering either useless without the other.

2.3.2 Diverging branches of excavation methodology

Carver (2009) identifies three methodological approaches of which the geometric schnitt and box trenching share similar traits of combining horizontal plans and vertical sections for documentation. These are in contrast to the third, stratigraphic excavation including single context planning, which operate primarily through plan drawings. Single context planning was first implemented in the UK through its adoption by the Museum of London as an extension of the Harris Matrix, and spread in the early 1980s to the Scottish Urban Archaeological Trust and the York Archaeological Trust through the initiative of Clark and Pearson (Clark and Hutcheson 1993; Pearson and Williams 1993). The principles are well described by Roskams (2001) and the method has proven its strengths, especially for deeply stratified sites. As Carver (2009) states, however, a sequence of single contexts without horizons and sections does not make our job of joining the fragments into a combined drawing any easier. It is indeed virtually impossible without the aid of a computer.

Stratigraphical or single context planning has two main objectives when it comes to spatial recording; divide everything into its different constituents or contexts related to prehistoric actions or events (cuts, fills etc.) to account for stratigraphy and chronology, and ensure the ability to collect and display these contexts according to the stratigraphical matrix or phasing. It is imperative to single context planning to aim at discerning as many details as possible in the horizontal plan, as opposed to recognising stratigraphy from vertical sections. To achieve this, a system is needed that allows for layering and, in digital terms, vector-representations of drawings so that we may overlay contexts and retain transparency between layers that would otherwise be blocked by the countless sheets of paper. Both GIS and CAD would allow for this approach. CAD would, however, allow this without the need to maintain an elaborate database, if the individual layers are named according to context numbers. CAD is also more equivalent to the process of finalising or 'inking' the drawings, rather than focusing on the creation of a cartographic map.

The schnitt or geometric excavation, on the other hand, has some other requirements. When excavating large sites with sparse stratigraphical information, the use of sections is '... a ruthless - but efficient – method' (Carver 2009, 117), which has the advantage of producing a three-dimensional model of a feature, but unfortunately the complete deposit is never documented in this destructive pro-

Figure 2.2: (VIDEO) Comparing box-cut and single context planning of posthole excavation in Denmark and UK. The Danish example is of the excavation of Viking Age longhouses in Jelling (Nielsen 2015; Holst et al. 2013), the UK example is the Lyminge Archaeological Project, University of Reading.
`https://vimeo.com/257346496/9587ee6c13`

cess. One would think that the three-dimensional aspect of geometric excavation would lead to CAD being the prevalent solution, but we actually see the opposite. GIS is widely used, maybe in part due to the geographically large areas of such excavations, which calls for a geographic representation, but maybe more so owing to the excavation method not explicitly producing a stratigraphical sequence, which must be represented as individual layers. The stratigraphy or phasing of contexts or features does not result from the layering, but must be assigned to the attributes of the individual features. GIS allows for elaborate data to be assigned context or feature numbers and relations to other larger structures for easy query and display. This is not possible in standard CAD solutions, which will hold only limited information about a geometric object or group of objects (Eiteljorg and Limp 2008). The choice of GIS or CAD, of course, also very strongly correlates to whether the focus of research is at a landscape-level or site-level – if our spatial features are considered geographies or geometries.

As an example, we can look at how both Danish and UK archaeology focus on recording the depositional history of a posthole (Figure 2.2). The questions we would usually pose include whether the posthole was part of a larger structure, if the post had burned, was pulled up or if it intersects with other features that would provide information regarding stratigraphy and chronology. In the UK, when adhering to the ideals of single context planning, the posthole would be approached from the top, emptied and recorded in plan through its individual contexts (post-pipe, packing and cut), and the sum of the contexts would constitute the posthole. It is generally considered a very reflexive excavation process, as it requires continuous evaluation of the nature of each context, and contexts are observed and recorded in their entirety, often as individual CAD layers of each context.

In Denmark, the starting point is usually based on initial surface observations, and a hypothesis that the feature is a posthole. This interpretation is then tested by making a box-section, effectively removing half of the posthole, to reveal a profile or section containing layers, which may be interpreted. Of course, either method is subject to adaptation according to the archaeological object in question, and in practice they sometimes converge by, for example, using a combination of stratigraphical top-down excavation and leaving half of the feature as a vertical section. In Denmark, the posthole is generally considered a feature that is part of a larger structure, a building, which is to be identified from similarities in the layers of the vertical sections. Similarly, Carver expanded on the Harris Matrix by introducing groupings of features and structures to single context planning (Carver 1990).

In either case, working with vertical sections has methodologically always been problematic. Vertical representations are not easily integrated with the horizontal plan drawing, and neither GIS nor CAD natively allows for this type of functionality. If at all digitised, vertical sections are often managed separately and in an arbitrary two-dimensional coordinate system, which is also why single context planning show much greater integration with these technologies.

2.3.3 Parallel threads of documentation

It would appear that single context recording and stratigraphical excavation experience a far better correlation between the methodological ideals and the technology and features available through GIS and CAD solutions (Figure 3). However, we arguably have a general problem of inherently incoherent and fragmented recording systems, with parallel series of data that of course tend to be correlated but not fully integrated. This is in part strongly related to a lack of software that covers all the needs of archaeological digital documentation, but perhaps even more so it relates to a digital methodology that is influenced by handling spatial data in a file system.

This is addressed by Wright (2011), who demonstrates how web technologies can help to integrate spatial data. Based upon the Web 2.0 philosophy and willingness to share data, and built on the semantics of the domain ontology for the cultural heritage sector (CIDOC-CRM) to allow for data query using the Semantic

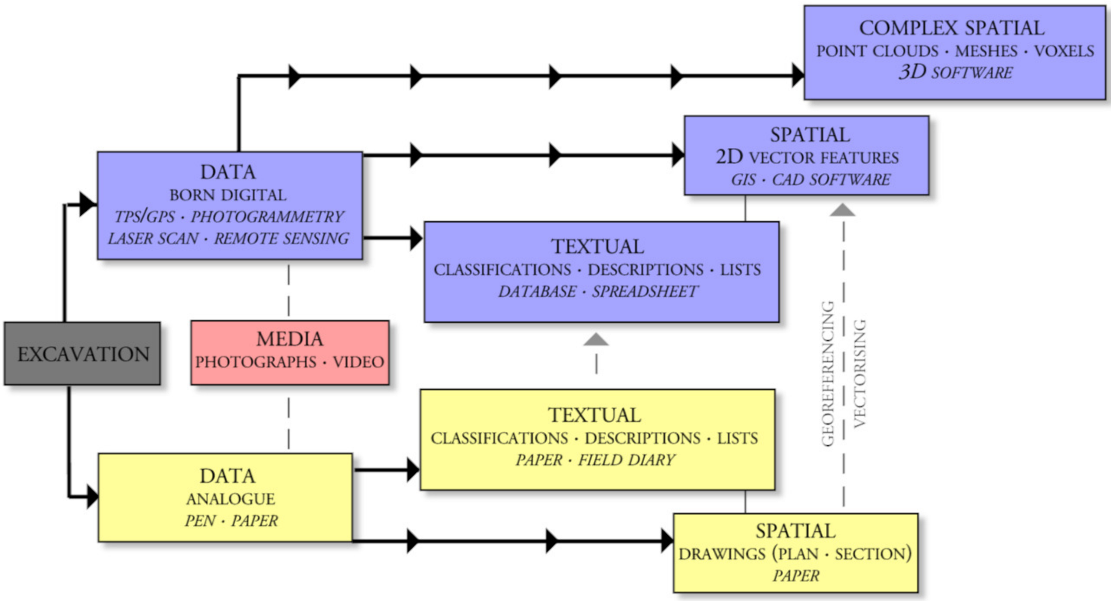

Figure 2.3: Parallel series of digital data. Textual, spatial and complex spatial.

Web Query Language (SPARQL), the project outlines the possibilities of integrating spatial data by translating vector data to comply with the Resource Description Framework (RDF) or RDF-triplets. The strength and versatility of the semantic web is currently being further explored through the GeoSemantic Technologies for Archaeological Resources (GSTAR) doctoral project by Cripps (2013), which is investigating how geospatial data can be integrated within semantic environments. This is an extension of The Semantic Technologies for Archaeological Resources (STAR) project between English Heritage and the University of South Wales (May et al. 2011; 2012; Cripps and May 2010) and the Semantic Technologies Enhancing Links and Linked data for Archaeological Resources (STELLAR) project, which includes the Archaeology Data Service (May et al. 2012).

The existence of these projects clearly demonstrates, that outside of specific research projects, trends in field recording shows data generally managed as parallel series of data, with spatial data managed by GIS, more or less detached from other non-spatial, textual data. This means that spatial data is rarely fully integrated into what we consider the archaeological documentation. Not only do we see parallel series of data, the issues are potentially increasing as new technologies and new data types are introduced. The advent of 3D documentation especially, necessitates preparations for a much broader display of data types and spatial representations.

2.3.4 The dynamics of spatial data

Looking back at traditional analogue field recording we may conclude that it generally fails to recognise or address the dynamics of spatial data. It is in fact a fragmented methodology, as traditional documentation principles were historically often based on field diaries, which used anecdotal approaches to document every minute detail concerning the progress of an excavation. In fact, we are dealing with a set of ideals for documentation, aimed at collecting the evidence to create a single, final interpretation - much in line with the ideals of single context planning. Consequently, the output of such strategies is characterised by rather static drawings based on an archaeologist's interpretation, not accommodating the subjective nature of a drawing and re-interpretation of such data. Instead they are considered a trustworthy representation of the observed.

Digital spatial data is distinctly different in many aspects. Firstly, it is more elaborate in its ability to balance the observation-proximate or photographic evidence against the archaeological interpretations. The differences are also closely related to the excavation methodology and workflow; how data is created in the first place and whether or not data is born digital or derived from other sources. In that respect, digital spatial data is extremely dynamic and derivative, and is often represented by fragmentary parts, which go into one or more adaptable composites to visualise a hypothesis. Much of the challenge lies in documenting this process, from data creation to post-processing, and handling how data, as well as hypotheses, develop over time. This of course, necessitates far more consistency, adherence to best practices and specialised skills.

Paradoxically, regardless of how fundamental it is to archaeological documentation, spatial recording was not always considered solely the task of an archaeologist. On the contrary, it was often considered sufficiently complex that it justified or even depended on the work of specialists. This usually included architects, professional land surveyors and map makers. The technological developments of field recording affected this pattern by making, for example, global navigation satellite systems and total stations more easily available and integrated with the digital tools used. Although things are rapidly changing, it is still often considered a specialist job to be able to handle surveying equipment or even GIS and CAD software, and perhaps even more so with the evolving technologies of digital photogrammetry and 3D recording. This has the potential to detach spatial data from the 'real' archaeologist, depending on how and where the interpretation phase is implemented. It also affects the post-processing, where fully exploiting the potential of the spatial record may boil down to the exchange of technical skills. As a consequence, two comparable methodological approaches have been put forward that address and support the formalisation of an ongoing flexible process of interpretation, and which act as a guide for the fieldwork as well as the generation of

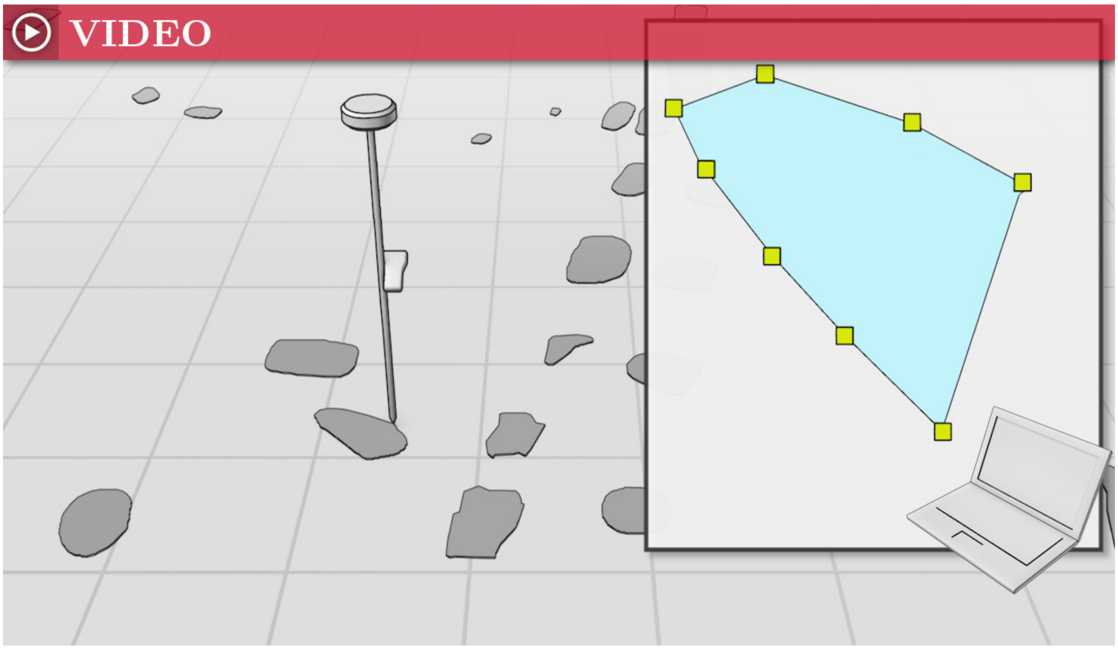

Figure 2.4: (VIDEO) The advent of DGPS systems meant that field recording could be done faster. Spatial data was 'born digital' and not derived from hand drawings. Illustration based on data from the Jelling Project (Nielsen 2015; Holst et al. 2013).
`https://vimeo.com/257346525/3bc202e8bf`

the spatial record: the Reflexive method by Ian Hodder (1997; 1999; 2000) and Martin Carver's evaluative archaeology (2003; 2009).

2.3.5 Spatial data 'born digital'

From a practical-technical point of view, one development more than any other has had a profound impact on digital spatial recording. The advent of centimetre precision Differential GPS (DGPS or RTK GNSS) revolutionised how we go about fieldwork – not least when viewed in the context of rescue archaeology (Figure 4). By its very definition, rescue archaeology is a matter of recording and documenting, usually ahead of some new construction that would otherwise destroy any archaeological remains. The process of working against the clock and within tight budgets is what makes up the bulk of archaeology today – not only in Denmark and the UK, but in most European countries where contract archaeology is a consequence of the ratification of the Valetta Convention for the protection of the archaeological heritage (Kristiansen 2009).

In Denmark, most excavations take place in rural areas by means of initial trial trenches followed by full excavation. The GPS was quickly accepted as a tool for doing fast and efficient recording, effectively drawing vectors by 'connecting the dots' of sequential measurements. The adoption of GPS provides an example of the (unintentional) standardisation of spatial recording related to implementation of new technologies. Danish archaeology is overseen by the Agency for Culture, and excavation activities are distributed among a number of local museums, each responsible for their region. Apart from some general guidelines regarding reporting, museums act as autonomous units, with methodologies varying according to traditions and excavators. GPS equipment has become a convenient household item at every museum, and through the development of ArkDigi (ArkDigi/MapDigi) for converting measurements into discrete objects (polygons and points) and the endorsement by the Agency for Culture of MapInfo as a GIS platform in 1998, these tools combined to form the 'standard way' of doing rescue archaeology. The positive side of this was of course the inadvertent normalisation of methodological practices. Naturally, it was also met with some opposition, as the quality of spatial data started to decline (Precht 2007). It became increasingly easy to do bad archaeology, reliance on poor-quality measurements sometimes leading to over-simplified recordings characterised by unrecognisable edged or circular drawings of features. Parallel to these developments, the focus on data management and analytical post-processing of excavation data by Andresen and Madsen led to excavation management systems, although not explicitly including the direct link to spatial data or GIS (Andresen and Madsen 1996a; 1996b; Madsen 2003). Unfortunately, these systems were never implemented on a larger scale, but succeeded in illustrating the challenges of data management when excavation data become digital and more dynamic.

Paradoxically, having the exact geographic position and being able to display a position and general classification on a map eventually became the accessible digital outcome for Danish archaeology. To some extent, this can be seen as a direct consequence of the 1984 inauguration and following developments of The Cultural Historical Central Register or the Danish National Record of Sites and Monuments (DKC) (Christoffersen 1992; Hansen 1992). Over the years DKC evolved as an administrative tool in cultural resource management, and archaeologists saw their work reduced to a dot on a map with only the most basic information, while there was no centralised place to store GIS data and basically no incentive to do complex spatial recording. In the period from 1984 to 2001, DKC was, however, accompanied by an annual journal of excavation abstracts alongside methodological papers 'Arkæologiske Udgravninger i Danmark/AUD' (Det Arkæologiske Nævn 1984-2001). This combination offered an accessible annual overview of excavations and their outcome, as well as sustained the exchange of methodological ideas.

The fact that a central database was never developed to accept spatial data led the individual museums to invoke their own 'standards' for storing and organising the vast amount of GIS data, usually related to the rest of the textual documentation only by corresponding feature numbers. The grass-root movement of MUD

(The Excavation Database of the Museums), which is a privately funded initiative supported by almost all the archaeological museums in Denmark, exemplifies the need to organise excavation data, but unfortunately still lacks the integration of spatial data (MUD 2014).

Archaeology in Denmark is still affected by the inherent problems of handling spatial data when it becomes digital. The fact that GIS and CAD were introduced at a time before it was considered a viable solution to use web strategies for organising and storing data meant storing spatial data in a file system. Anyone who has worked with the proprietary file formats of the leading commercial GIS suites like MapInfo and ArcGIS know that each map layer is represented by not only one file (.tab, .shp, etc.), but a handful or more additional files, often leading to hundreds if not thousands of interdependent files that are a challenge to handle consistently. It is, however, also related to the level of preparedness to respond to new technologies by rethinking existing methodologies.

By contrast, in the UK commercial archaeology has influenced digital and methodological developments in other ways (Everill 2012). Although the competitive element can be criticised for risking the devaluation of archaeology by letting the cheapest tender offer win the contract, on the other hand, the commitment to compete results in an incentive to try out quicker, more efficient and by all intents and purposes better and more flexible approaches (Everill 2012; Kristiansen 2009). In this day and age such solutions are often digital. The incentive to do faster and more efficient documentation within rescue archaeology is common, but in one key aspect the two countries differ. Where the Danish museum archaeology tends to work towards one, albeit only basic and mostly textual, central recording of sites and monuments, the different UK excavating institutions have more or less developed their own tools and frameworks for integrated documentation. Interestingly, online public dissemination and accessibility appear to play a significantly larger role in UK archaeology, and is usually a key aspect to the different recording systems.

Beyond commercial archaeology, digital documentation in the UK was pioneered as long ago as the early 1980s through research projects like the Heslerton Parish Project (Powlesland 1998). The comparably longer tradition and more (successful) extensive use of remote sensing and geophysical survey probably expedited the development of techniques for handling a wide array of spatial representations (e.g. geophysical raster representation) and Powlesland and May further extended the integration and testing of new technologies for field recording through the DigIt project (Powlesland et al. 2006, Powlesland and May 2010).

2.3.6 Digital documentation frameworks

One of the most prominent examples of a UK recording system, which also had its beginning in the 1980s, is the Integrated Archaeological Database (IADB), originally developed by Stead and Clark at the Scottish Urban Archaeological Trust (Stead 1988). The development was later taken up by Rains who brought it to the York Archaeological Trust in the late 1990s. With the retirement of Rains its future is uncertain, but it is currently in use by many universities and commercial units. What made IADB special was its integrated capabilities, allowing for dynamically creating vector excavation plans alongside the textual classification.

Another example is Framework Archaeology, a collaboration between Oxford Archaeology and Wessex Archaeology, aimed at handling the documentation from the excavations at Heathrow and Stansted. The project-focus of how people inhabited landscapes places great emphasis on interpretation in addition to recording, and develops a historical narrative as the site is excavated (Andrews et al. 2000). The project includes a Framework Free Viewer for Windows computers, which allows users to investigate and browse through the archaeological documentation deposited at the Archaeology Data Service (Framework Archaeology 2009), as well as through a Web GIS interface (Framework Archaeology 2011; 2014).

The ARK Archaeological Recording Kit by LP Archaeology differs by being entirely web-based, and does not require anything but a web-browser and network connection, and in addition can be easily customised through its open source architecture (PHP). Building on a spatially enabled database (MySQL) and data management for many kinds of data, such as images, GIS data, 3D reconstructions, sound and video, ARK is also aimed at readily sharing and publishing archaeological data to the web (Eve and Hunt 2008).

These, in addition to other projects, illustrate the level of development of different recording frameworks characteristic of UK archaeology. Not that such development is in any way limited to the UK. One Scandinavian example is the IntraSIS Intrasite Information System developed by the National Historical Museums in Sweden. Built as an extension of the capabilities of the ESRI ArcGIS product suite, it is designed to manage and structure geographical as well as textual data, and is now in use by almost all major archaeological institutions in Sweden, as well as the Copenhagen Museum and Historic England. Its strong impact in Sweden and endorsement by Historic England for one thing demonstrates an increasing tendency towards uniformity and homogeneity in the documentation technologies applied.

Common to both UK and Danish archaeology is the appearance of field manuals that aim to ensure comparable and consistent recordings, such as the Archaeological Site Manual (Museum of London Archaeology Service 1994) and the Danish Felthåndbogen/The Field Manual (Schou Jørgensen et al. 1980), a now-discontinued subscription service to individual papers on methodological and technical field practice topics. In Denmark, the privately run MUD-organisation has come to play a significant role in its efforts to develop and maintain a central database as well as define standards and structure for archaeological data, textual and spatial (MUD 2014).

When it comes to digital spatial data, MUD issues general guidelines for Danish archaeology, but they are limited to structuring and organising GIS data, primarily how to handle the vast amounts of GPS-data in a file system. The lack of central management of spatial data is, however, an area of real concern. The SARA project, led by the Agency for Culture, is expected to include some degree of GIS capabilities in a new central cultural-historical database scheduled for implementation in 2016 (Slots- og Kulturstyrelsen 2015), which may address some of these issues.

In the UK, the establishment of the Archaeology Data Service (ADS) in 1996 has played a significant role in the development of archiving solutions for digital data, ensuring its durability and availability (Huggett 2006). But even more so have the series of Guides to Good Practice produced by ADS and Digital Antiquity actually influenced and formalised standards in digital recording of archaeology (Archaeology Data Service and Digital Antiquity 2015).

At an international level, it is worth noting the European initiatives within the ARIADNE framework and the INSPIRE protocol, which support the development of infrastructure between distributed datasets and provide guides for best practices as well as technical specifications for interoperability of archaeological data, including spatial information (McKeague et al. 2012; INSPIRE; ARIADNE).

2.4 Trending Documentation Technologies - Pursuing Different Ideals

Migrating from analogue to digital excavation plans is fairly easy using GIS and CAD as they are rather similar in style and function. At its core, all you have to do is to scan paper plans, georeference or align them in the software and vectorise them. The key advantage is of course the ability to seamlessly arrange and manage layers of documentation, but vectorisation offers new ways of embedding information into the drawn features as well. Early opponents did, however, object to the rigidity of a system where you could no longer work with features that had uncertain boundaries or faded into each other, and the loss of the artistic freedom of hand drawing. This was contradicted by those who saw the opportunity to enforce a more reflexive archaeology, giving archaeologists an incentive to search for and recognise features more precisely. It serves very well to demonstrate how the drawing to some extent was (and still is?) considered an aesthetic product of the documentation rather than a scientific document. An untenable situation, if the ideal of documentation is the aim for the most reality-proximate representation of the observed and interpreted archaeology.

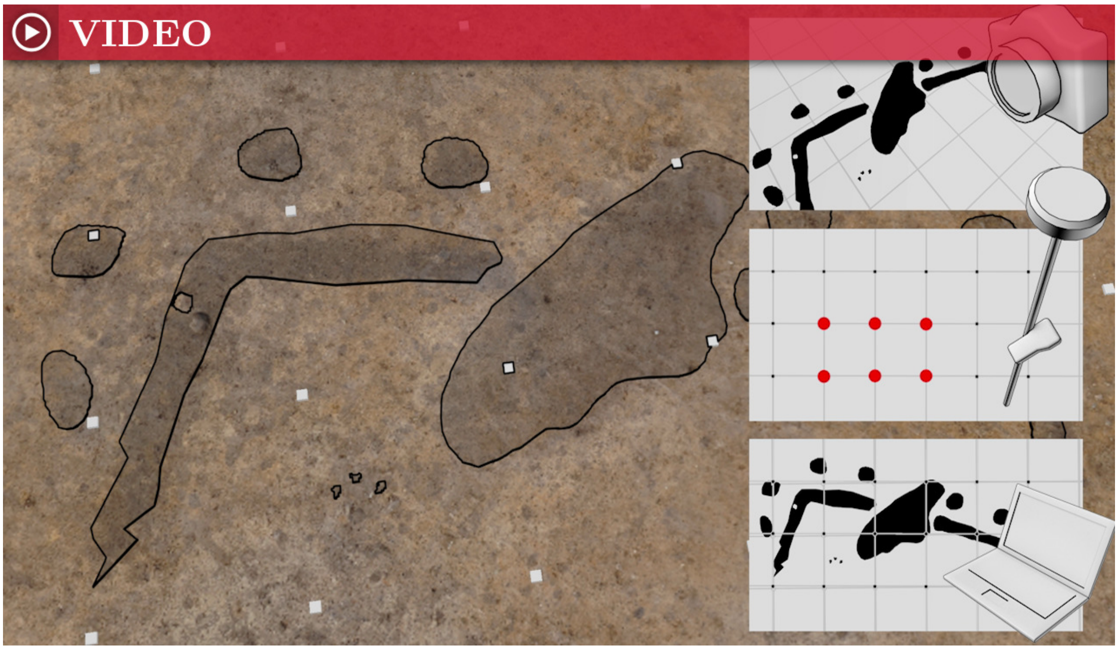

Figure 2.5: (VIDEO) Conceptual illustration of the documentation of an archaeological excavation; photo-rectification based on measured control points transforms photographs into a type of field recording data, which may be used as basis for drawings and vectorisations. Illustration based on data from the Jelling Project (Holst et al. 2013).
`https://vimeo.com/257346544/653f44f471`

2.4.1 Photogrammetry and photo rectification

Much more of a methodological challenge became evident as technological developments meant that digital photos became an easy, quick and affordable way of documenting an excavation. The archaeological community, however, fairly early on realised that digital photographs have to be treated differently, as they are not directly equivalent to analogue hand drawing. Digital photos represent a new data type. Of course, the scanning of hand drawings as a basis of digitising is a well-known technique - but raster images in the form of photos are something different. First of all, they have to be manipulated to be usable for documentation, rectified (Scollar 1998; Johansen 2003) and embedded with geographic information (Figure 5). This clearly leads to some concerns as to the validity and derivative nature of what would otherwise be considered a very objective documentation. On the other hand, it evidently offers new possibilities of a different level of documentation detail, quality and authenticity. Some excavation projects have actively developed frameworks to combat the risk that photos could potentially shift the archaeological focus away from interpretation, towards mere descriptive, and basically undermine the value of documentation (Berggren et al. 2015; De Reu et al. 2013; 2014; Forte et al. 2015).

2.4.2 Real-time 3D vector documentation

Figure 2.6: (VIDEO) Conceptual illustration of the documentation of an archaeological excavation; real-time 3D vector data acquisition using for example optical ranging with total station or point tracking by radio waves through RF positioning systems. Illustration based on data from the Alken Enge excavation (Holst et al. in press).
`https://vimeo.com/257346554/1f29c9e930`

Some noteworthy research has gone into retaining the characteristics of a hand drawing by means of real-time 3D vector documentation, perhaps primarily as a response to the overemphasis on photographic representations and the supposed lack of interpretation or the notion of absolute objectivity (Figure 6). This has the clear advantage of being more or less directly comparable to historic documentation – the line drawing being a well-known concept. A few commercial products have emerged, such as the Digital Laser Pantograph by ArcTron Ltd, Termite for Rhino3D and Nikon iSpace (Schaich 2010; Hyttel 2012; Avern and Franssens 2012). Although their technological approaches are different, combining mechanical and optical techniques, the outcome is basically a conversion of consecutive 3D measurements of the positioning of a probe or a 'pencil' in 3D space into 3D polylines real-time, instantly resulting in a visualisation on a connected laptop computer or tablet, which is not that different from DGPS. Although the notion of supporting the reflexive and interpretative incentive is sound, and it works really well on flat surfaces and walls, it is not an all-round solution. Most 3D objects, such as standing structures, especially if they are not rectangular, are very difficult to translate into a 3D vector without subjecting some kind of projected view, which unfortunately brings us straight back to the projected 2D drawing. It does have the advantage of interfacing directly with GIS or CAD, and is born digital and integrated, and from a data collecting and documentation point of view – more data are usually better. In this case, however, there are challenges in using these methods for recording interpretations as well as observations.

2.4.3 3D Laser scanning

The technological development of total station theodolites has made them increasingly faster and easier to operate, and they have become an important asset to archaeological field recording in situations where sub-centimetre precision is required; something that DGPS currently does not provide. Operating by combining very precise vertical and horizontal angle measurements with infrared distance measurement between the instrument and a reflective prism, it provides real-time calculation and logging of points in a three-dimensional local or global coordinate system, and often integrates with DGPS systems. The automation and advancement of reflector-less measuring is, however, breaking down the divide between total station and dedicated laser scanners, and both are able to produce 3D point clouds

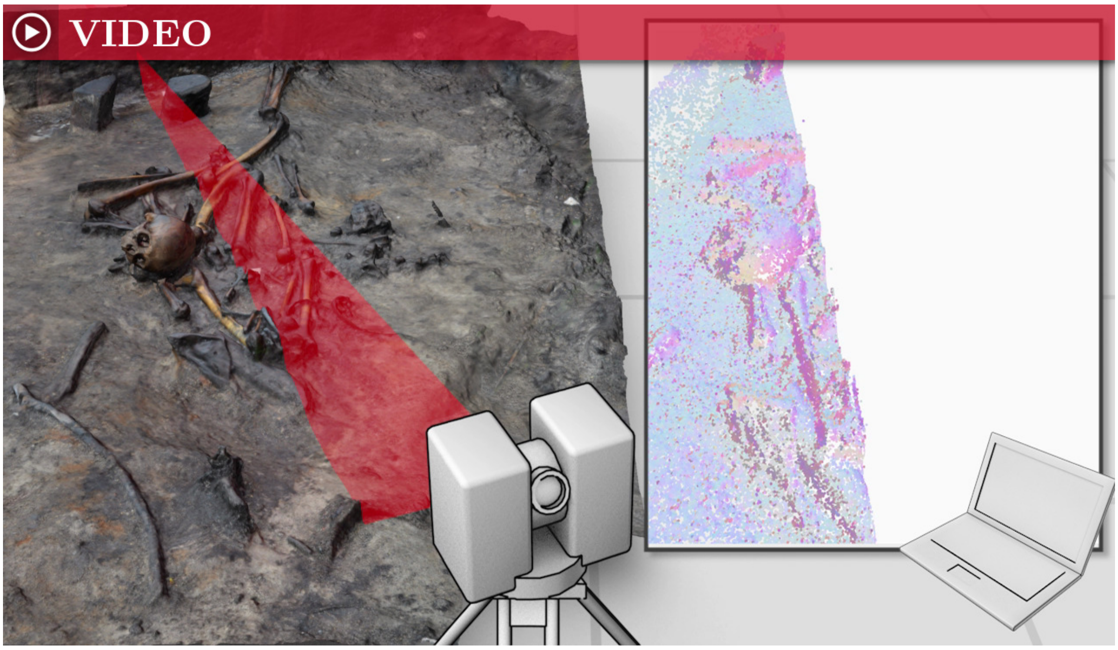

Figure 2.7: (VIDEO) Conceptual illustration of the documentation of an archaeological excavation; generating 3D point clouds by 3D scanner. Illustration based on data from the Alken Enge excavation (Holst et al. in press).
`https://vimeo.com/257346558/ef06568e06`

A 3D scanner usually involves a laser beam for measuring distances, producing a point cloud with a density defined by the angular distance between each measurement. This will often result in hundreds of thousands if not millions of 3D points in a point cloud, and is usually ideal for either detailed recording of architectural features and entire buildings or minute artefact details (Figure 7). It does, however, suffer from line-of-site issues, and usually requires several geo-referenced setups to cover all obstructed areas. It does, however, not integrate well with line-drawing and interpretation, but acts as an observation-proximate snapshot (English Heritage 2011).

2.4.4 Structure from Motion and Range Imaging

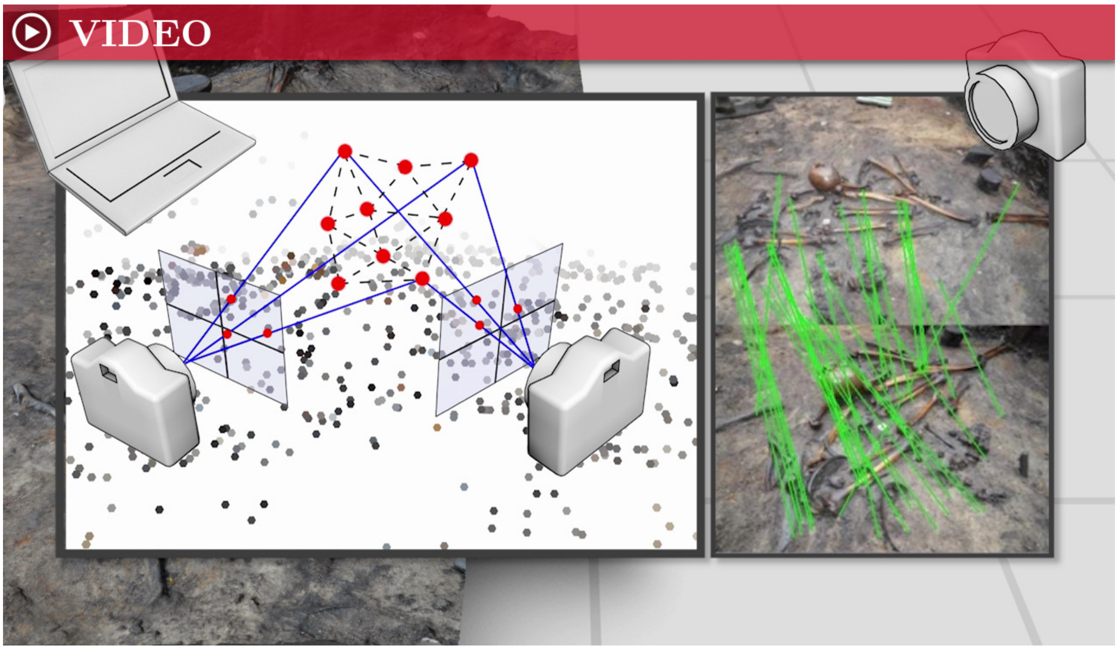

Figure 2.8: (VIDEO) Conceptual illustration of the documentation of an archaeological excavation; generating 3D textured meshes by Structure from Motion. Illustration based on data from the Alken Enge excavation (Holst et al. in press).
`https://vimeo.com/257346569/41b78ea3ca`

At present, an increasing array of techniques exists that allow easy, digital, spatial 3D representations of objects or entire scenarios. Some of the more prominent examples are the different photogrammetric techniques - especially Structure from Motion (SFM) (Wu 2011; 2013; Agisoft). SFM allows the creation of highly detailed 3D models based on photos alone, and is currently seen as a cheaper, faster and more flexible alternative to 3D scans, using dedicated 3D scanners (De Reu et al. 2013; 2014; Ducke et al. 2011; Koutsoudis et al. 2014; Pollefeys et al. 2001; Berggren et al. 2015; Powlesland 2014) . The technology is based on the discipline of range imaging and basically works by principle of parallax. Several photos of an object or a scene, taken from different angles, are automatically compared and matched two-and-two by similar feature-points to calculate the camera movement between individual photos and combined to a position in an arbitrary three-dimensional frame of reference. In turn the 3D positions of individual points are calculated, and potentially georeferenced from fix points in the photos (Figure 8). In its most basic form, the output of the method is a point cloud of 3D points, in essence comparable to the output of a laser scanner. However, the similarities end with the fact that the data output usually includes colour or even bitmap texture information, and that an entire scene is covered in one relatively quick photo session. The time it takes for a computer to calculate the 3D model poses a problem regarding a seamless integration with field recording, as it is likely to introduce a bottleneck in the workflow, caused by waiting for a result before the excavation can continue. It is, however, something that may be addressed through distributed and high-performance computing (Stott et al. in press). Different software, such as Agisoft Photoscan or Meshlab additionally allow for the generation of detailed meshes that are either coloured by vertex or texture mapped by face. Finally, perspective distortions (Escher effects) that would normally arise from ordinary photogrammetric rectification of not perfectly flat surfaces, are overcome using SFM to create orthophotos, which tie in nicely with usual archaeological 2D documentation.

2.4.5 Ideals of archaeological documentation

From the point of having created our primary spatial documentation, using any of the technologies above, we arrive at the challenges of integrating it alongside our textual classification data. Common to the data produced by these technologies is the very derivative and generalised nature. As illustrated above, an increasing array of digital recording frameworks exist, which support different levels of spatial integration (Figure 9). One aspect is, however, apparent in all these solutions: that methodological traditions and technological advances are not easily combined. One key aspect, which is commonly only addressed to some extent, is the revision of what the ideal of archaeological documentation is, and what the actual end-product of our archaeological excavation is supposed to be. Take for instance SFM-generated, highly detailed 3D models with perhaps millions of vertices and high resolution textures, which are often essentially reduced to rectified orthophotos for vectorisation, as equivalent to a drawing, effectively disregarding the high level of spatial and geometric information inherent in a 3D point cloud or mesh. We choose to reduce data to something we know how to handle. The data representation in 3D documentation is so vastly different and complex that it is currently next to impossible to compare to older excavation data, if not somehow transformed into something that is 'backwards compatible'. It is difficult to justify only looking ahead and focusing on new technologies without taking proper care to bring the past documentation up to speed. This is not just because archaeology, by definition, is focused on the past. Already many resources have gone into digitising and vectorising old excavation documentation, and the prospect of having to do it over to bring it up to a comparable standard with 3D documentation - if at all possible - may appear as a futile attempt at keeping archaic spatial data alive, again and again.

The fact is that spatial data that is born digital tends to be very derivative. It is shaped by a series of generalisations brought on by new methods and post-processing techniques, which produce a primary source material based on calculations and estimations we have very little knowledge about. A paradox, which relates to a profound lack of metadata and particularly paradata associated with the creation of our digital spatial data.

2.5 Moving Towards 3D: Challenges of Spatial Integration

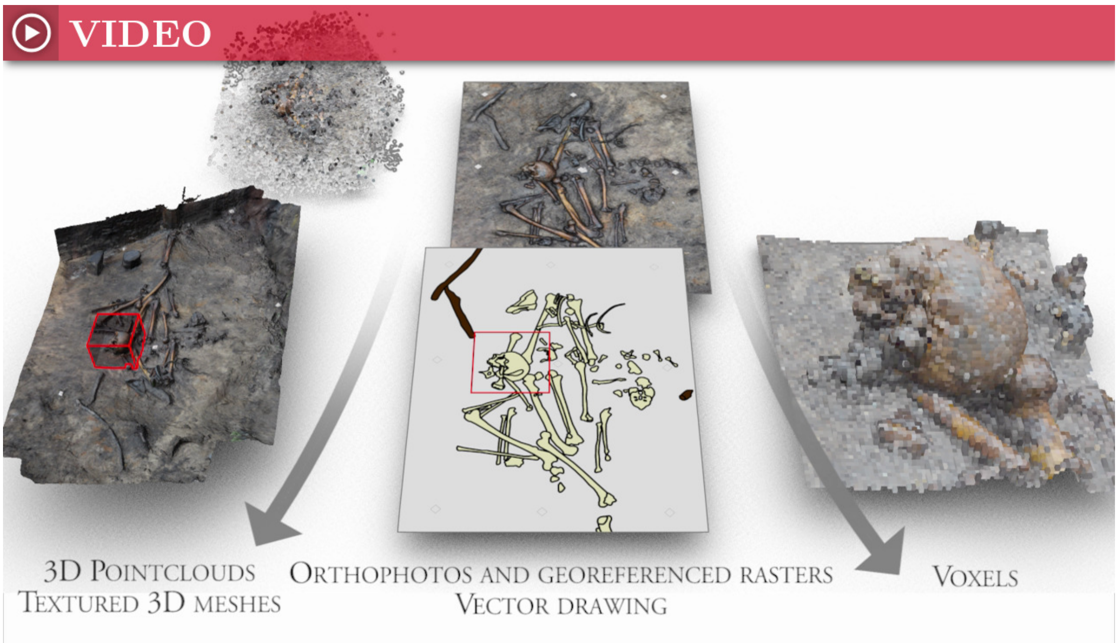

Figure 2.9: (VIDEO) Different data representations. The mainstream raster and vector representations are being supplemented by new types of primary data such as point clouds and derived 3D meshes on one side, and voxel representation on the other. Illustration based on data from the Alken Enge excavation (Holst et al. in press).
https://vimeo.com/257346591/3f61a79a34

2.5.1 Different ideals meeting 3D photogrammetric documentation

In dealing with the ideal of archaeological documentation, it is in part a question of how we perceive the archaeological record and in part the issues of absence and incompleteness and whether ’the total record’ actually exists. This is illustrated by the classical controversy between Petrie, who argues for the idea of the selective record, and Pitt Rivers’ idea of the total record with respect to the collection of archaeological evidence (Lucas 2012). On the other hand, spatial recording, naturally, lies at the centre of both ideals, and a common limitation is what we know as the paradox of excavation – that in order to record and document, we destroy the primary record. This does not apply to non-invasive archaeological prospection and remote sensing, of course. As we have seen, the recording strategy is deeply rooted in traditions and in a propagating documentation ideal - be it single context planning or schnitt/planum. In either instance, the notion of recording the past should perhaps be rephrased as ’the action of recording the process of investigating the past’. Arguably, the way we assure the value of archaeological spatial recording, is by accounting for the documentation process; meta- and paradata concerning the tools and the methodology applied, so that we may evaluate its validity and authenticity.

In comparing field archaeological traditions in the UK and Denmark, the different methodological approaches clearly relate to an ideal with consequences to our archaeological praxis – the role that documentation plays and the requirements it must meet. In traditional and single context archaeology, interpretation on site is not encouraged if not including post-processual reflexivity (Hodder 1997; Lucas 2001; 2012) but focus very profoundly on a final end-product of the excavation; a summary of the conclusions reached. Single context planning is as much an intellectual thought process of interpretations of what took place in the past in terms of sedimentary formations. This approach is, however, hampered by non-sedimentary events that do not relate to human activities, like biological processes – potentially undermining the premise for single context excavation.

The Danish excavation methodology over the course of the last decade has seen a wide acceptance of the more arbitrary schnitt, focusing less on the use of contexts. Instead, the excavation is considered an iterative process, by which the collection and evaluation of spatial data, primarily ’features’, continuously improves and adds to the interpretation, and guides the excavation forwards. The excavation is often primed by a research agenda similar to the one proposed by Carver (2003; 2009) and the photogrammetric documentation is considered an observation-proximate control of hypotheses. Instead of interpreting the archaeological record as the product of archaeological contexts, the documentation itself becomes the framework of information, and organised by an agenda of visualisation. This is particularly clear from excavations by Aarhus University in the period 2002-2016 at sites such as Skelhøj, Jelling and Alken Enge (Holst et al. 2013; Holst & Rasmussen 2013; Jessen et al. 2011; Holst et al. 2018). In targeting an illustration – in fact planning our documentation during the excavation on the basis of how we expect to be illustrating our results in the final report - the excavation is continuously being evaluated and the hypothesis is constantly questioned. As a consequence, a reconceptualisation of the basic documentation units is needed to dynamically support the iterative process and accommodate new spatial data both during the excavation and in post-processing. Basically, this means building the documentation from a series of data collections and documentation events, essentially recording the timeline of the documentation and interpretation process, rather than basing it on archaeological contexts (Jensen 2012).

As a comparison, the UK principle of single context recording actually fits well with the possibilities of photogrammetric recording, building up 3D models of individual units, interfaces or surfaces. It may even be the best way of documenting, considering that arbitrary sectioning, combined with photo-documentation, tends to basically record the excavation strategy and the location of cuts and sections. Individual contexts as 3D representations, on the contrary, directly reflect the archaeological record, or at least the surface of it, and much less the excavation layout. Single context archaeology is inevitably also being challenged by the new methods. Numerous individual contexts must be put together to create a 3D representation; an overall picture of 'what you can see'. In fact, the ideal of reaching a final interpretation within single context planning may be what is leading archaeology, particularly in the UK, to countless examples of visual reconstructions and applications of visualisation technologies. From a dissemination stand point and as an added bonus, this combines very well with the elaborate traditions of public outreach within British archaeology.

Interestingly, the two methodologies appear to approach each other and converge in dealing with the ideals of how we want to use the collected spatial data. Both focus on the ability to work with arbitrary surfaces; it is how both define their basic units of documentation. The main difference lies in whether the surfaces are actual physical entities or derived from visualisations or interpretations. Danish arbitrary surfaces will usually constitute physical sections or schnitt, which are available for scrutiny both during excavation and through observational, photographical documentation. The same section - or any other - could be constructed post-excavation in a single context excavation from the collected context plans, although based on the interpreted contexts as the primary evidence.

Arbitrary surfaces may be thought of as the middle ground of documentation principles, where single context planning and strict stratigraphical approaches meet the arbitrary pragmatic sectioning of features. In combination with 3D documentation, a less rigorous approach to single context recording is possible, as stratigraphical information is embedded within the model, through the absolute recording of elevation in a 3D-model. At the same time, arbitrary surfaces are very distracting to three-dimensional recording, as they tend to depict the layout of the excavation rather than the actual archaeological features or contexts. On the other hand, 3D-recording of physical, arbitrary surfaces inherently delivers some of the stratigraphical information that might otherwise be neglected in a large, open-area excavation conducted through arbitrary sectioning.

2.5.2 Was GIS or CAD the right choice all along?

Related to the ideals of digital archaeological documentation, whether we are talking about single context planning or schnitt, we are in fact dealing with a common basic assumption; that GIS or CAD delivers what we need in terms of vector-representation and raster management of observations and interpretations in archaeological recording. What is perhaps not immediately recognised is that the tools and software in question were developed alongside the archaeological methodologies during the 1980s and 1990, and that the tools in fact helped shape our methodology. This is, however, also what to expect, working with the available tools.

Today GIS can be considered the standard for archaeological spatial recording (Wheatley and Gillings 2002; Conolly and Lake 2006), but in fact it is hardly ever questioned and it is actually debateable whether GIS or CAD was the right choice for archaeology all along, and if it really deserves the wide acceptance we see today. GIS and CAD of course demonstrate some unique capabilities. For example the ability to make our spatial data 'globally aware' and to fit it into a broader, geographic and landscape-analytical perspective, combined with the collective representation of layers, which fits very well into the framework of stratigraphical or single context archaeology. But it comes at a cost. Fundamental to archaeological field methods is an ongoing struggle with the abstraction of transforming the interpretation of a three-dimensional world onto a two-dimensional surface, be it paper or computer screen. GIS has until very recently had problems representing true 3D in a way that actually corresponds to how our field methods operate. Everything is represented as a topside projection onto a geographic model. Since archaeology is not only about getting an overview map, but actually often a matter of extracting information from a three-dimensional representation, GIS never quite seems to solve that. From the perspective of an open-area site with perhaps thousands of postholes, especially one in Denmark, where the focus is on box-cut, one cannot ignore how much work is going into describing and correlating vertical sections or profiles, but how little it actually integrates into the standard GIS representation. Traditionally plane and section, horizontal and vertical documentation are managed separately, and only brought together through post-processing and setup of combined illustrations. The fact is, our traditional excavation methodology is based on two-dimensional units, documented in a vertical or horizontal plane. In that regard, the norm of documentation - regardless of methodological traditions - is the abstraction of a 3D spatial representation comprised of 2D fragments. We

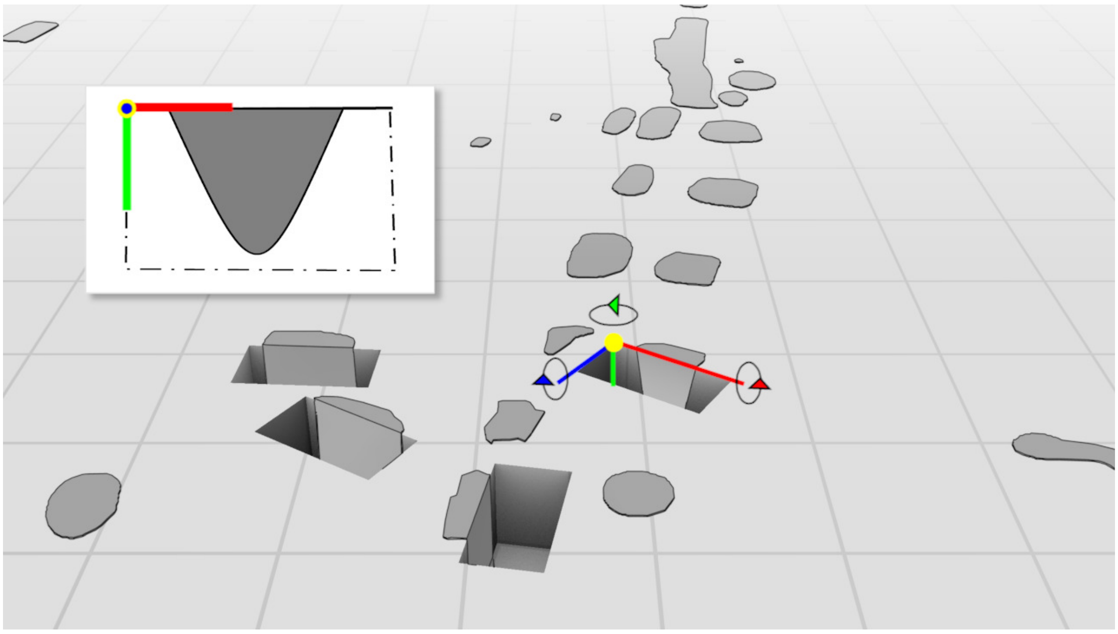

Figure 2.10: Conceptual illustration of how the Danish excavation methods could gain from a system that allows 3D georeferencing of individual 2D fragments. Illustration based on data from the Jelling Project (Holst et al. 2013).

would see georeferenced plan drawings with vertical section drawings (raster or vector) detached and in an arbitrary two-dimensional coordinate system.

In this scenario, what GIS does not deliver is the ability to essentially georeference rasters and vectors in 3D. Currently, different workarounds are employed to convey the appearance of vertical sections in, for example, ArcScene, but it is not straightforward (Katsianis et al. 2006; 2008; Forte et al. 2015; Berggren et al. 2015; Landeschi et al. 2016). Usually, a raster image is georeferenced by defining the world coordinate of the top-left corner of the image, along with pixel size and rotation in relation to a world coordinate system. In fact, although not in use, the GeoTIFF specifications include x, y and z coordinates 'in anticipation of future support for 3D digital elevation models and vertical coordinate system' (Ritter and Ruth 2000). An archaeological information system that would allow for defining translation and rotation (origin, scale and three rotational axes) would effectively allow us to raise our two-dimensional sections (raster or vector) and integrate horizontal and vertical plans in a flexible visual representation that supports our current and historical excavation methodology (Figure 10)

As mentioned, the hand drawn excavation plan translates extremely well to a digital vector equivalent, which is fundamental to GIS and CAD. This direct conceptual correlation has undoubtedly helped accelerate the migration to GIS and CAD, and in combination with the possibilities of assigning attributes and performing analyses on vector representations, it has proven to be a very powerful tool. But is it possible that adhering to the concept of line drawing using vectorisation, and focusing on the use of GIS and CAD, is actually what has impeded the full integration of spatial data in the archaeological documentation, especially in the context of 3D documentation?

To most archaeologists, the line drawing is what separates mere descriptive observation from actual, interpretative or reflexive documentation, and removing it would undermine the value of documentation (Berggren et al. 2015; De Reuet al. 2013; 2014; Forte et al. 2015; Hodder 1997; 2000). But is it a necessary element of digital documentation, or a product of misconceptualised digital migration? It is worth considering if vector representation is actually how we want to use 3D models, or if it is just what current GIS solutions allow us to do.

The biggest challenge in using 3D documentation is how to do so on its own merits and not by reference to traditional 2D line drawing. This cannot be understated. We also need to learn how to effectively work with 3D polygons, if that is the goal, and deal with the way GIS uses projection and interpolation to conform vectors to 3D mesh surfaces.

2.5.3 Addressing the challenges of digital spatial integration

The matter of workflow has become an important issue in archaeological field work. Technology increasingly acts to structure the framework and activities that take place during field recording (De Reu et al. 2014; Berggren et al. 2015), but as we have seen above, the challenges of spatial data management must also be addressed. Since 2009, the '3D-Digging at Çatalhöyük' project has explored numerous techniques for 3D recording of the excavations at this important Neolithic site in Turkey, and it is one of the best documented examples of how complex spatial data may be integrated both in terms of recording and managing 3D structures (Forte 2014). Other projects have demonstrated how 3D models may be subjected to visual analysis within GIS environments (Katsianis et al. 2006; 2008; Landeschi et al. 2016). It is understandable, why these developments are taking place within GIS frameworks, as it is most likely due to the trending convergence of functionalities related to 3D. The dividing lines between GIS and CAD are becoming increasingly diffuse, as each continuously add functionalities from the other. AutoDesk has, for example, issued numerous 3D and GIS enabled variants of their CAD-suite including AutoCAD Map 3D, which, as the name implies, seeks to fulfil the needs of 3D map-making. ESRIs flagship ArcGIS has developed to include the ArcScene application and its latest version of ArcGIS Pro supports the integration of 3D point clouds, meshes and 3D polygons together with its native data management capabilities. Even dedicated 3D modelling software such as AutoDesk 3D Studio Max 2015 is now supporting point clouds as a native geometry type, emphasising the link to real-world 3D recorded objects. Central to this development are also several freeware or open source projects like Meshlab, which provide the interoperability and processing capabilities needed to use 3D data efficiently. From a data management perspective, development of the ADS 3D Viewer will provide visualisation capabilities and integrate with archived archaeological 3D data (Galeazzi 2014).

The application of 3D GIS at Çatalhöyük is currently relying on ArcScene for the management of different 3D documentation objects, units or layers to visualise stratigraphy, combined with 3D vectorisation of the interpreted contexts and features. These polygons can then be extruded to model the 3D interpretation as solid objects, and more clearly visualise building elements (Berggren et al. 2015; Forte 2014; Forte et al. 2015). The shortcomings of relying on GIS as the technical platform is, however, again manifested in the way ArcScene handles vectors. Like ordinary GIS, ArcScene is based on a principle of projecting and interpolating vectors, but in this case not onto a geographical geodesic model like a sphere or cylinder, but onto a mesh surface. Depending on the resolution of the surface model and numbers of vertices in the vector, it will only be able to conform to the surface to a certain degree, leading to lines and polygons that either float above or intersect with the mesh (Dell'Unto 2014; Kimball 2016). This raises a question of the value of continued use of vector geometries as conveyors of archaeological classification, when in reality they are limited to the quality of the underlying mesh and the interpolation and projection algorithms used by the software.

If we are to fully exploit the rich detail of 3D documentation we must adapt to the premise of new datatypes such as point clouds and meshes. In effect we need the ability to directly classify these types of data according to our interpretation (Wulff and Koch 2012). This allows us to work with data in a completely different manner. It is actually straightforward to do a simple classification of, for instance, a point cloud or a mesh from a vector drawing by simply projecting the two data types onto a plane, and execute a point-in-polygon algorithm (see Figure 11).

An important issue is, however, the lack of systems that meet archaeological criteria regarding visual representation of vertical and horizontal, integrated with data management and strong semantic data models. A system that combines an incredible range of scale, from representations of the smallest things such as samples of pollen and individual pieces of charcoal, through to artefacts, features and buildings as well as intra-site spatial distributions. GIS, for example, often lacks the full data management capabilities needed when we want to represent a complex hierarchical archaeological data structure. Data management support is virtually absent in other types of spatial management systems, such as dedicated 3D-modelling software and to some extend CAD, and it very clearly accounts for the need to apply and even develop specialised management systems, as we have seen for example with IADB. Understandably, there is much focus on these tech-

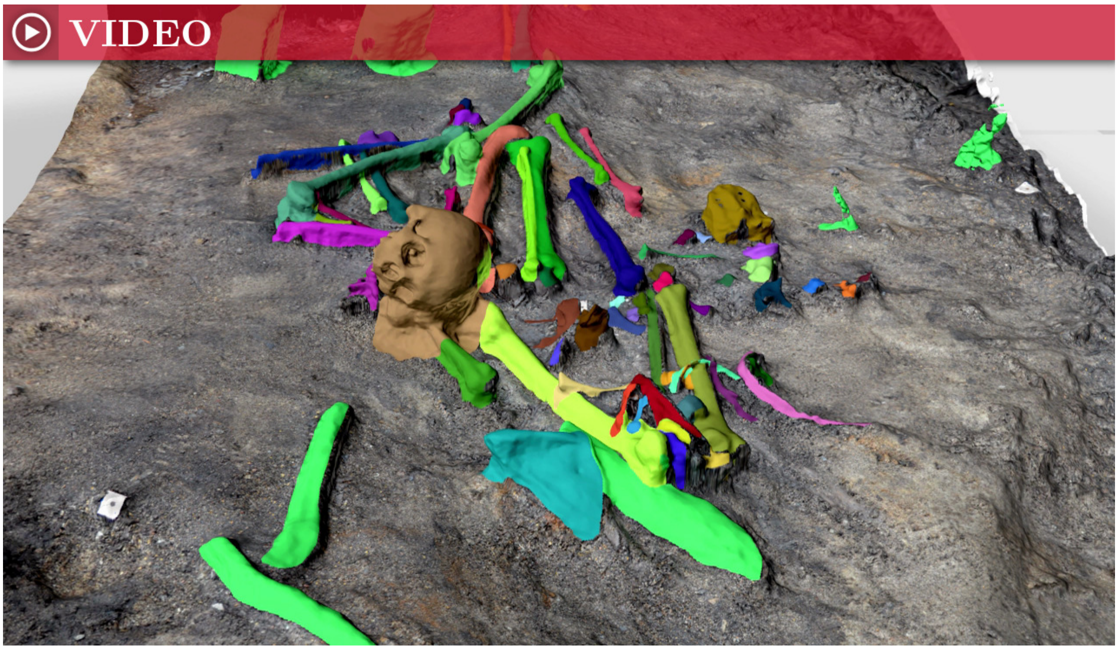

Figure 2.11: (VIDEO) Conceptual illustration of how classification of point clouds and meshes could be done. Also demonstrating preview of online web 3D viewer, which supports selection of classified 3D meshes (in development by the author). Illustration based on data from the Alken Enge excavation (Holst et al. in press).
`https://vimeo.com/257346594/916ab57e8f`

nical issues related to new methods of spatial recording, and it is easy to blame technology and lack of tools that fit the archaeological workflow, but in fact it is only half the problem. It is arguably equally as much an issue of lack of conceptualisation of new types of data in the documentation process and to a large extent a matter of neglecting to conceptualise archaeological methodology onto new digital approaches. As drawing conventions are necessary to communicate our interpretations consistently in a 2D framework (Roskams 2001, 136) , so are conventions or conceptualisations of the 3D recording. We need a migration of an analogue frame of conceptualisations into a digital equivalent, and technical solutions that combine our textual and interpretational data and spatial data, taking into account the dynamics and heterogeneity of new types of spatial data; GPS-measurements, photogrammetric techniques, vectors, rasters, 3D point clouds and meshes. Tools such as 'X-bones' (Isaksen et al. 2008), which was actually developed a relatively long time ago, illustrate how it is possible to transform spatial data into a visual representation and embed semantic information, in this case for the analysis of human bones. Excavation projects in northern Greece have also demonstrated how it is possible to extend existing GIS systems and use ArcScene as a framework to include all aspects of spatial, conceptual and semantic informa-

Figure 2.12: (VIDEO) Conceptual illustration of how voxels may be used for representing volumes of archaeological context rather than surfaces. Illustration based on data from the Alken Enge excavation (Holst et al. in press).
`https://vimeo.com/257346617/af0b79d441`

tion, such as excavation units, contexts, rasters and vectors, and even advanced 3D symbology (Katsianis et al. 2008). Looking beyond archaeology towards other disciplines such as chemistry or medicine, we find that 3D visualisation of semantic information is something that has been worked on for years, and which with modifications could be applied to archaeology (Hanwell et al. 2012).

To fully exploit the semantic, analytical and data management capabilities of 3D documentation within archaeology, we must be open to other types of data representations as well, which may not necessarily fit into our usual concepts of observation and interpretation, but act as a hybrid. One such hybrid, which is actually also a hybrid of raster and vector representations, is the voxel model – or volume pixels. It has previously been extensively used in medicine as the framework of visualising MRI scans, but has also found its way to archaeology, especially through the extensions available for open source Grass GIS (Orengo 2013; Lieberwirth 2008a; 2008b; Bezzi et al. 2006). It is potentially less abstract and conceptually much more in correlation with our physical object, which is probably why voxels have also been widely used for data from ground-penetrating radar (GPR) – in fact blurring the lines between above/below ground archaeology (Leckebusch 2003).

In 3D printing, physical voxels can be different shapes and sizes (see Beale and Reilly this issue). When working with volume pixels in the context of 3D visualisation (Figure 12), we must also choose a level of generalisation - the size of each little cube - depending on the size and amount of detail in our documentation. It is then a matter of projecting and applying a 3D grid to our 3D point clouds, effectively merging and splitting everything into neighbouring cubes. Voxels have several advantages over a point cloud or a complex 3D mesh. First of all, depending on the size of the grid, it reduces the data amount significantly. Instead of recording x, y and z coordinates, the relative position in the grid and an ID is sufficient. Additionally, voxels can be stored as a sequence or stack of raster images or slices. Handling large amounts of image-data very quickly and efficiently and maybe even compressing it is something computers do very well. The voxels can even inherit the classifications and semantic information from our vectorisations, allowing us to do spatial analyses and easily perform arbitrary cross-sections, as we are no longer dealing with simple surfaces, as in a mesh, but actually have some depth and volume to work with.

In terms of documentation ideals, only time will tell to what extend new spatial data representations such as voxels will affect archaeological methodology. It could very well be a game-changer, as it is conceptually totally different from our usual approaches. Instead of identifying and working with borders, surfaces and interfaces, we would actually be working with the volumes of 'stuff', allowing interpolation of layers and contexts between sections, and in effect changing the paradigm of documentation ideals. At the same time it could help to break down the separation between sensory data such as geophysical surveys and archaeological observations and interpretations. This, however, still requires work into technologies and excavation methods that provide effective means of acquiring the necessary spatial data.

2.6 The Dichotomies of British and Danish Archaeology

Regarding the dichotomies of archaeology in Denmark and the UK, this article has presented some of the key differences between the two geographic areas, in part attributed to the historical legacy, political agenda and heritage management, and method development over the course of a century of field archaeology. To this day, many Danish archaeologists would characterise British field methodology and adherence to single context planning as dogmatic rather than by design, and hardly seen as versatile tool. As Carver (2011, 22) states regarding single context planning: 'How strange, then, that for all this evangelical reverence, the package still remains confined to a rather narrow base, both ethnically (British), economically (well-funded), and typologically (urban excavations)'. There is no doubt that the character of the sites being investigated – shallow, extensive settlements vs deeply stratified ones – are defining for the excavation approach – as it should be. The right tool for the right job. This is, however, not what single context planners advocate in their yearning for an integrated, unified discipline with common goals, ideals and methods worldwide. In Denmark, for example, most urban excavations are recorded as stratigraphic excavations rather than by strict single context planning, which as a recording method is arguably much more versatile (Carver 2011).

Apart from the dogmatic and typologically determined methodology, there is a valid point in seeing the convergence of CAD and single context planning as mutually influential on how single context planning developed, and how technology to some extent became defining for a recording ideal based in part on technological preconditions. Excavation plans become split into individual two-dimensional horizontal objects, stacked with only a context number as reference. On the other hand, GIS with its lack of native 3D support yet superior handling of attributed classification data, affected how settlement archaeology developed, but also delivers a digital documentation legacy of detached vertical and horizontal plans.

2.7 Conclusion

The advances in archaeological field documentation have, among other things, been described as a prelude to a paradigm shift in a scientific revolution (Kristiansen 2014). This equally applies when we address the consequences of new data types and new methodologies in archaeology. New questions and concerns are inevitably raised; is archaeology at a threshold, at risk of abandoning the traditional interpretative and reflexive incentive, for the sake of a documentation that appears to correspond more closely to the observed 'truth'? From a technical point of view, how do we even handle and integrate digital representations of reality and interpretation, which differ profoundly from what traditional archaeological documentation is based on? Do new spatial recording technologies and methods potentially solve or further complicate existing issues, with parallel tracks of fragmented and detached spatial and textual documentation.

Despite having undergone a decade-long digital transformation, much of the archaeological documentation we see today is based on the same basic principles and, generally speaking, a direct migration of the traditional, analogue recording techniques to a digital equivalent. Arguably, new technologies are being applied to the existing methodologies with very little focus on re-defining what we actually want to do with our spatial data. Adaptation is rarely done in a particularly coherent way and data are often reduced to fit within the archaic framework of archaeological concepts. Furthermore, the adherence to the use of line drawing is potentially what is currently deferring an actual paradigm shift in the development of field- and documentation methodology.

Addressing these issues from the point of different methodological traditions and corresponding ideals of documentation, this article has demonstrated that

3D documentation techniques are indeed increasingly accepted and applied despite limitations to the technical frameworks such as GIS or CAD. Even more interesting is the potential of Structure from Motion and similar techniques for archaeological field recording. It may constitute a new methodological framework, bridging the gap between different field archaeological traditions; a middle ground of documentation principles, where single context planning and strict stratigraphical approaches meet the arbitrary pragmatic geometric sectioning of features.

Although different methodological approaches clearly relate to an ideal with consequences for our archaeological praxis, excavation and documentation methodologies are not necessarily restricted or determined by the available technology. Most importantly, modern archaeology tends to be sufficiently open-minded and in support of the continued experimentation that is required to manage new and different methods for data acquisition and spatial documentation and representation.

There is one thing the willingness to test out 3D documentation has shown us – that the propagating ideal of field recording is prepared for change, and not limited to what GIS and CAD allows us to do. We strive for something more, and the technological limits and boundaries of imagination are continually pushed in that direction.

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3

Evaluating Authenticity Authenticity of 3D Models in Archaeological Field Documentation

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Abstract: 3D documentation advocates for a new workflow with a more 3-dimensional reasoning, allowing for the utilisation of 3D as a tool for continuous progress planning and evaluation of an excavation and its results. Similarly to the general use of models to form hypotheses, it is possible to use 3D models as spatial hypotheses of ongoing excavations. This allows a spatial conceptualisation of a hypothesis as a virtual reconstruction, and to combine it with an increasingly detailed and photo-realistic image-based 3D recording.

Instead of relying on seemingly arbitrary levels of 'trustworthiness' or 'related to fact' this chapter proposes a re-conceptualisation of the authenticity concept. Not used for evaluating if objects and replicas are authentic or not, but applied as a measure of documentation quality - 'how effected by interpretation are our observations - and how open are they for reinterpretation?', and not least 'how was our documentation created in the first place?'

To interpret and visualise through 3D modelling requires strict guidelines and regard for the separation of observation and spatial hypothesis, and insurance that the one is not mistaken for the other. In combining 'reality data' with 'model data', evaluating the level of authenticity becomes paramount to the quality of excavation documentation.

Authenticity may be used as a concept and as a tool in the archaeological documentation workflow allowing us to augment the scientific quality of excavation data. This chapter presents an approach to integrating this new level of documentation detail into excavations through conceptualising levels of generalisation and authenticity.

3.1 Introduction

The use of photorealistic and photogrammetric techniques to create 3D models of excavations is increasingly becoming an accepted approach to documentation practice in field archaeology. Whilst archaeologist seem happy to embrace new technologies for field documentation they tend to use them, either for traditional recording purposes (such as computer-aided drawing), or by letting technology dictate the documentation outcomes, for example, by creating interactive 3D models, which are incompatible with traditional means of documentation. Paradoxically, the use of 3D visualisation in archaeology is neither a relatively recent or sudden phenomenon (Reilly 1988, 1992). The advent of 3D representations as archaeological documentation characterises a departure from the conventional spatial abstraction of a 3-dimensional world to a 2-dimensional piece of paper. As a consequence, the basic epistemological foundations for archaeological recording are affected, calling for a revision of not only the general workflow of excavations, but a re-evaluation of those dichotomies inherent to field archaeology, such as that between observation and interpretation. With 3D documentation, we are increasingly dealing with photorealistic representations of archaeological excavations, and the time, place and basis for archaeological interpretation is changing. The far-reaching consequences touch upon core dichotomies of archaeological science, where particularly the polarisation of objectivity and subjectivity has affected archaeological thinking for the better half of a century (Kristiansen & Rowlands 2005, Shanks & Tilley 1987). However, as stated by Shanks and Tilley (1987): "Archaeological theory and practice as labour in the present completely transcend this artificial division, labour which draws past and present into a fresh perspective, a perspective which serves to rearticulate their relationship". In this regard, accepting 3-dimensional photorealistic documentation also means accepting that it is not free of bias. To an extent, the ideal of objective truth through empirical falsification (Popper 1959), reproducibility, and testability set forth by the scientific method is hindered by the destructive nature of the archaeological excavation and the derivative nature of the archaeological documentation.

In this chapter, the term reality-proximate is used to describe the creation of photorealistic representations of the observation event, taking into account the limitations of detail, and distancing the visual replication from a notion of objective recording. Rather than focusing on objectivity and subjectivity, this chapter will discuss the dichotomy between observation and interpretation in archaeology in the light of the new paradigm of 3D photogrammetric documentation, and it proposes a way of managing 3D observation data alongside reconstructions and visualisations. The excavation of three archaeological sites in Denmark; Skelhøj, Jelling and Alken Enge, reflects the impact of technological developments on the archaeological workflow during the last 15 years, and show how a conceptualisation of authenticity may be applied to address the evaluation of documentation quality.

It is proposed that the use of 3D documentation encourages us to adopt a new workflow with more 3-dimensional reasoning, allowing the utilisation of 3D recording as a tool for the continuous monitoring of progress and evaluation of an excavation and its results. Just as in the general use of models to form hypotheses, it is possible to use 3D models as spatial hypotheses within an ongoing excavation. This allows us to visually realise or spatially conceptualise our hypothesis as a virtual reconstruction and to combine it with our observational data.

Usually our interpretation is characterised by the delineation and characterisation of features and finds, be it line drawing on paper or vectorisations in GIS or CAD, but in a 3D representation, this makes much less sense. We are actually able to interpret and visualise through 3D modelling of a spatial hypothesis, rather than working with lines and sketches. This in turn requires strict guidelines, and regard for the separation of observation and spatial hypothesis, and assurance that the one is not mistaken for the other.

Finally, this chapter presents experiences gained from combining reality data with model data in the case of the Jelling excavations. The field-recording principles applied accentuate the necessity of continuous evaluation of the integrity and validity of empirical data, and illustrate how the concept of authenticity becomes paramount to assessing excavation documentation. This is particularly the case when documentation is combined with 3D models and reconstructions at the boundary between research and dissemination.

3.2 Observation and interpretation in archaeology

If there is one characteristic, more than any other, that permeates the discipline of field archaeology, it is dichotomy. As Carver (1990:45) puts it: "Archaeologists who work in the field suffer from split personality". Carver obviously refers to the conflicting traditions of field work, which diverged in the early youth of the discipline, in the 19th century. Briefly put, British archaeologists Pitt-Rivers (1887) and later Barker (1977) were among the most prominent proponents of the empiricist approach, based on an idea that every minute detail matters and should be recorded in the field, and that an archaeological site should be treated as a system of deposits and formations processes. This is related to the processualist approaches of New Archaeology (Binford & Binford 1968, Trigger 1989). On the opposing branch, Petrie (1904) and Wheeler (1954) saw that attempting to record every fact about everything was futile and useless without an overall goal or research motivation, which is what inspired the structuralist and contextualist approaches, focusing on the site as text to be read, rather than deposits to be described. These dichotomies exist to this day, albeit they are converging, perhaps not least due to developments in technology. Lucas (2001:10) points to the fact that field archaeology by the 1870s was characterised by "experience, presence in the field, as a critical guarantor of scientific validity". Incidentally, the advent of contract archaeology and the factor of competitive tendering based on price, favouring preservation by record, saw the growth of archaeologists specialising in fieldwork, meaning that fieldwork became more separated from the broader interpretative process. The archaeologist now took the role as a technician, whose job it is to retrieve data from the field, resulting from “an ideology founded on the assumption that data collection is independent of interpretation” (Lucas 2001:12). In contract archaeology, the dichotomy stems from a matter of politics which separates fieldwork from interpretation, and where the empiricist seek to record as much as possible, while researchers and universities state that actual meaning is determined by posing relevant research questions – making data a research asset. The challenge or “Archaeological Value” lies in combining the two (Carver 2003, Carver 2009).

When dealing with archaeological excavation recording and documentation, using a seemingly arbitrary concept like authenticity may appear to make very little sense, especially if we claim to aim for “objective” documentation. Nonetheless, one might argue that the dichotomy of the objective (Malmer 1980) vs. subjective (Shanks & Tilley 1987) lies at the heart of evaluating the authentic, but it tends towards an unproductive opposition between realism and constructivism (Madsen 1995, 2003). The processual or “new” archaeology of the 1960s never questioned if we are able to describe anything objectively, but rather than the positivistic realism of measurements and observations, asserted that archaeological interpretation could come to objective conclusions via the ability to pose questions and formulate what we want to investigate (Binford 1964:426). In particular, the ability to uncover the regularities of human cultural behaviour was in question. The post-processual archaeology of the 1980s, however, saw that every description requires interpretation and reflects the subjectivity and viewpoint of the archaeologist. By this notion, authenticity, which usually relates to a seemingly arbitrary level of “trustworthiness” or “related to fact”, reflects the views, bias and possibly the social/political circumstances of archaeology and the archaeologist. The influence of society “appears to remain one of archaeology’s permanent features” (Trigger 1989:380), which is why it is necessary to account for context when evaluating authenticity in archaeological documentation. This in turn forces the archaeologist to explain, if not theory and method, at least the choices made during the excavation process, as well as the rationale behind them. It is considered a serious problem if an archaeologist is unable to “look out beyond the individual context or unit they are excavating, [as they] will not be able to deal with interpretative issues that involve other contexts and other sets of data” (Hodder 2003:59). In particular, the interpretative and reflexive element is of interest to Hodder who pointed to the “momentary, fluid and flexible” existence of excavation methodology by the late 1990s (Hodder 1997).

Advances in archaeological field documentation in the new millennium are a continuation of the development of computer applications in archaeology throughout the 1980s and 1990s focusing on the use of quantitative methods in archaeology. In particular, photorealistic and photogrammetric techniques for creating 3D models of excavation situations are fast becoming a common approach to documentation practice, and call for a re-evaluation of the inherent dichotomy of interpretation and observation in archaeology (Berggren et al. 2015, Forte et al. 2015, De Reu et al. 2013, Forte 2014, Powlesland 2014). Compared to previous paradigm shifts, which were characterised by confronting ideas and ideals of how to do archaeology, the significant technological advances have only just recently become identified as a prelude to a paradigm shift in a scientific revolution (Kristiansen 2014, Huggett 2004). This inevitably raises questions and concerns whether archaeology is at risk of abandoning the interpretative and reflexive incentive, for the sake of a form of documentation that appears to correspond more closely to the observed "truth". Drawing in particular, is often seen as essential to archaeology and "part of a hermeneutic system that acts to both initiate and reinforce the knowledge-creation structures of the discipline" (Bateman 2006:74), but it may also be considered a remnant of analogue documentation traditions, which becomes challenged by the need for the ability to handle and integrate digital representations of both reality and interpretation. Evidently, Hodder's fluid archaeology is becoming even more pronounced, as the clear distinction between observation and interpretation turns increasingly fluid and traditional concepts become entangled. By direct consequence, evaluation of authenticity gains new relevance as the documentation itself, rather than the object or artefact, attains authenticity. Generally speaking, archaeologists who share a goal of measuring the past as accurately as possible are also the ones who are most interested in pursuing authentic archaeology.

3.2.1 Photogrammetric documentation

One technological advancement stands out more than any other as "a tool that underpins our notion of the objectivity of the recording process" (Bateman 2005:192). In the last decade, archaeologists have overwhelmingly adopted digital photography (Morgan 2014; Morgan & Wright 2018). At the same time, digital photos have increasingly become one of the primary sources of archaeological documentation, in addition to - or as basis for - digital delineation of the interpreted features and contexts. Digital photos have become an easy, quick and affordable way of documenting an excavation. The documentation process at the excavation of the Bronze Age barrow Skelhøj (2002-2004) in Southern Denmark exemplifies one such early application of digital photography in excavation documentation (Holst & Rasmussen 2013). It also illustrates how the archaeological community, fairly early on, realised that digital photography had to be treated differently, as it is not directly equivalent to analogue hand drawing.

First of all, digital photos must be manipulated to become usable for documentation: rectified (Scollar 1998, Johansen 2003) and embedded with geographic information. This clearly leads to some concerns as to the validity and derivative nature of what would otherwise be considered very objective documentation. On the other hand, it evidently offers new possibilities of a different level of detail, quality and authenticity. In the case of Skelhøj, documentation workflows were deliberately adapted to combat the risk that photos could potentially shift the archaeological focus away from interpretation, towards the mere descriptive, and basically undermine the value of documentation. To accommodate concerns of losing the interpretative incentive and whenever possible, parallel series of photos were taken – an observation series with the prepared archaeological features, and an interpretation series where an archaeologist's interpretation would be scratched or sketched into to soil (fig. 1). This of course only works for soil-archaeology, as opposed to building recording, but was based on a notion that the observational photos are somehow a more objective form of documentation that would allow us to revisit or re-examine our archaeological data, and therefore represent a set of data, which was less "disturbed" by interpretational bias.

As claimed regarding the reflexive archaeology at Çatalhöyük: "The goal is to make the excavation process virtually reversible in a simulated environment at levels ranging from laptop computers to virtual immersive systems" (Berggren et al. 2015). Being well aware that the collected data - the photos - are never more objective than the archaeological process as a whole (Bateman 2005), the archaeologist still has to choose and prepare the different surfaces and objects for documentation. It is an encounter, not just observation, albeit active or interpretive observation (Lucas 2001). On many levels, digital photos represent different resolutions of evidence, and 3D photogrammetric techniques such as Structure from Motion represents a further extension of the inherent properties of digital photos. This is due to their ability to provide visualisations and representations, which appear as photorealistic and geometrically authentic representations of real-world objects and scenes, which consequently is evolving to become an ideal of documentation. The key point here is that 3D photogrammetric techniques represent rather than accurately reproduce some aspect of reality. The documentation is still as subjective as ever but, perhaps worryingly, disguised as unbiased by its photorealistic appearance.

If, for the sake of argument, we state that the level of authenticity is in direct correlation with the amount of interpretation and assumption in its representation of reality, photographic evidence must clearly be more authentic than a delineated interpretation. But more authentic in this case does not necessarily mean that it

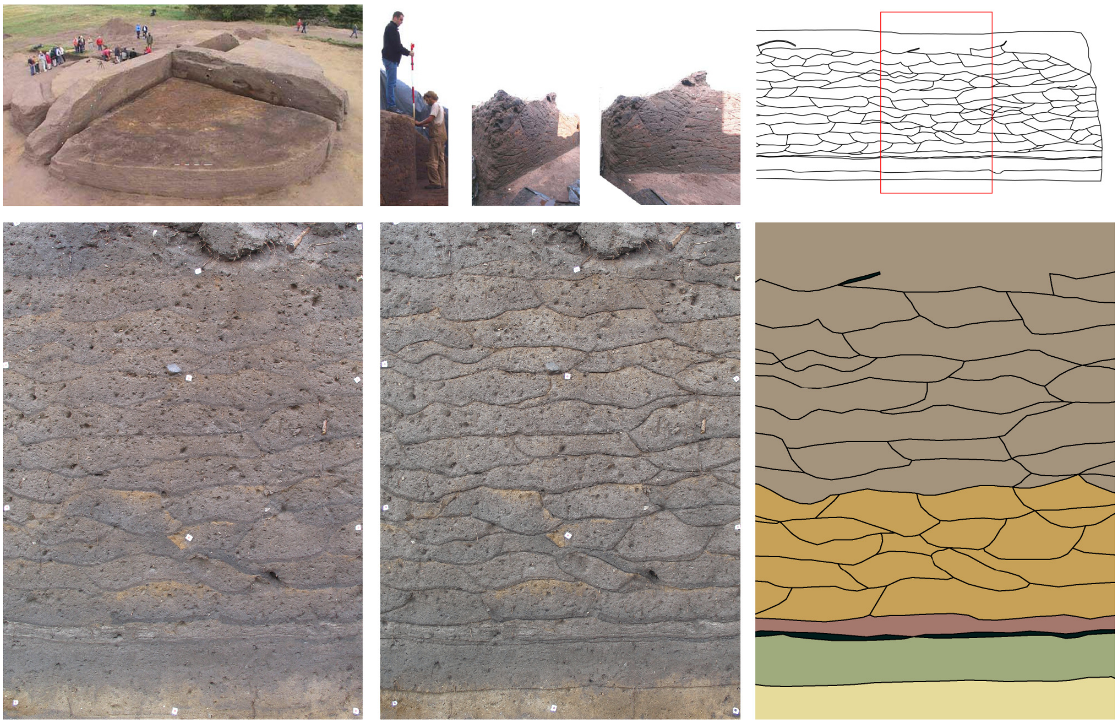

Figure 3.1: Skelhøj. Documentation of turf structures in a Bronze Age barrow, using observation photos and interpretation photos as basis for rectification, mosaicking and vectorisation. Photo: Peter Jensen.

makes the greatest contribution to knowledge. One would think that a 3D model or a photo is easily understood and requires fewer preconditions, but rather it lacks explanation and interpretation to fully extract the embedded information. What a 3D model does provide, however, is an immediate representation of reality. Instead of knowledge and skills of abstracting from the 2-dimensional drawing or photo, we see a malleable canvas, which we can interactively explore in a non-predetermined way.

Maybe the biggest Achilles heel of post-processual archaeology is our inability to agree on even the most trivial factors, such as classifications or the description of fill and colour of a context or layer in a section. As Madsen (2003:14-15) illustrates, the descriptions are so dependent on prior experience and knowledge, that two people with the same basic understanding, but different experience, will rarely reach the same conclusions. The work of the less experienced archaeologist may appear as the most authentic, as the lack of prior knowledge prevents differentiation between the important and the less significant; they tend to describe "what they see". It is, however, difficult to integrate as common fact into our documentation, and emphasizes the dichotomy between rationalism and pragmatism - if knowledge comes before experience or if experience precedes knowledge. Even implementing something as objective as colour-codes is still limited by various factors, ranging from different lighting condition to the individuals' perception of colour. Post-processual archaeology inherently necessitates an evaluation of the authenticity of the classification and description according to the "human factor".

One of the postmodern traits of post-processual archaeology is the disappearance of the limits between disciplines, and the disappearance of faith in knowing the one truth (Johnson 1999:166), leading archaeologists to accept all understandings of the past as equally valid and equally authentic, but not necessarily equally objective.

3.2.2 "New-objectivity"

In 2003 Madsen pointed to the discrepancies between the geologist's and the archaeologist's approach to the interpretation of a soil section, and how different professional backgrounds and perspectives shape the documentation outcome. Naturally, an archaeologist will focus on traces of human activity, while the geologist is looking for geological processes. In either case, the issue is not how to draw or describe, but the act of identifying the abstract notion of something, which is not a physical entity like an object or artefact, but a context of some previous human or natural action. 10 years later, in addition to the philosophical implications of a new paradigm of 3D photorealistic documentation, this "new-objectivity" has arguably a profound methodological impact on several aspects of field recording. It offers a new conceptual interface or structure of visual representation, which forces us to construe how an object in a 3D representation relates to a feature in the reality of the past. The new tools affect the interpretation flow and how we perceive and identify the relation between objects, and redefine the interdisciplinary preconditions of archaeology such as collaboration with geologists.

The archaeological investigations in the wetlands of Alken Enge between 2012 and 2014 revealed thousands of scattered human bones, dated to the Early Iron Age, lying beneath approximately two meters of peat on an old lake bed (Hertz & Holst 2015, Holst et al. 2018). This set the stage for an interdisciplinary collaboration involving, amongst others, the Department of Geoscience at Aarhus University (Søe et al. 2017).

The excavation conditions were challenging; excavating a bog 2 meters below the water table of the neighbouring Lake Mossø. From the onset, a workflow and documentation pipeline was set up, consistently based on photogrammetry and Structure from Motion using VisualSFM and Agisoft Photoscan (Wu 2011, Agisoft 2016). This way, every documentation unit, context, and arbitrary plan or section was photo documented, 3D modelled, ortho-rectified, printed, drawn, classified and vectorised. Beyond the collaboration with osteoarchaeologists and anthropologists, the presence of geologists and their very different approach to the

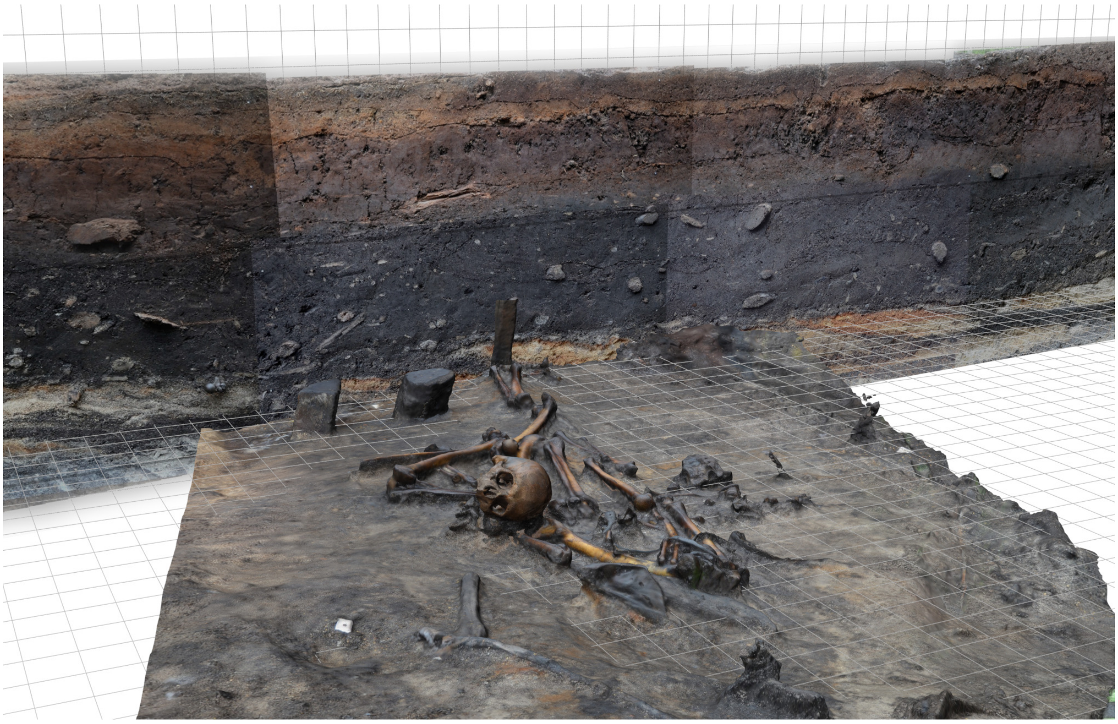

Figure 3.2: Composite of 3D Structure from Motion documentation of human bones, alongside geological section in Alken Enge.

research questions came to be of great value in explaining the prehistoric events (fig. 3.2).

Furthermore, the challenge of combining the archaeological and the geological interpretation of the same reality demonstrated, how 3D models and photorealistic documentation may act as a common language in this discourse. The excavation saw the development of a common language, exchange of terms across disciplines and illustrated how interpretations were not necessarily linked to one profession alone. The boundary between geology and archaeology became fluid, and at a general level a method development took place where datamining and comparison of data became key to understanding the facts. Most importantly, this cross-discipline exchange of knowledge was not limited to or hindered by different interpretations of the same reality, because the issue was no longer a disagreement of classifications, as Madsen (2003) implied. The premise for the "new-objectivity" of 3D photogrammetric documentation is not one of classification, but accounting for the level of authenticity and validity. How open to interpretation are our observations and what is the quality of our documentation?

3.2.3 Derivative and generalised: para- and meta-data

One of the keys to integrating 3D photogrammetric documentation in archaeology lies with the realisation that 3D models are part of a process, much like the formation processes which create the archaeological record in the first place. The premise for this type of documentation is that our so-called primary data is derivative in nature, and its validity depends entirely on our ability to account for how data was created and evolves over time. We all work from assumptions that are rarely well described or even questioned. The formation process of our 3D documentation, or rather the para- and meta-data does exactly this. By estimating and evaluating claims of certainty or documentation quality, it may be possible to augment the scientific quality of data - and use authenticity both as a concept and as a tool in the archaeological documentation workflow. In this way, we are in fact equalising evidential value and testing hypotheses - rather than engaging in a truth-seeking quest.

The most enticing promise of archaeological 3D documentation is that, in theory, we should be able to create a reality-proximate visual representation of reality. And in fact, we should be able to "re-excavate" on the computer at a later point in time, and potentially engage other colleagues in the interpretation process. This breaks with the traditional premise or paradox of archaeological excavations – that it is a destructive discipline that cannot be redone and which destroys the original source material. The fact that this approach actually enables and encourages us to correct or revise both the observation and the interpretation data, facilitates a more dynamic approach to documentation, instead of delivering that one interpretation – the synthesised and condensed report of an excavation.

We know that all visual data is derived - a generalisation of something more detailed to begin with, and must undergo some process to get from the real world into our digital representation. First of all, we must account for multiple parameters related to the excavation process; how was the excavation planned and executed, and what where the documentation events that make up our bulk raw data (Jensen 2012). Secondly, the data processing needed to get from photographs to 3D models must be documented. The increasingly complex calculations needed, perhaps even by proprietary closed-source software, poses an issue in this regard. It makes the documentation process much less transparent, and any inaccuracies and systematic errors may potentially sneak into our primary documentation when we trust a "black box" and its invisible algorithms to process data.

Arguably, it is by conceptualising levels of generalisation and authenticity of these steps of the digital documentation that we are able to more coherently integrate new levels of documentation detail into our excavations. If we develop procedures for measuring the authenticity of 3D photogrammetric documentation through an evaluation process, we may break with the objective realist stance commonly applied to 3D models. This is, however, not to assume that the authentic is a utopianism to be achieved. The concept of objective documentation is far less important than authentic documentation, and in this regard, authenticity equals the quality and detail of representing the observed. To express it more explicitly; the level of authenticity may be expressed as an equation of approximation, which includes all available para- and metadata related to the documentation events. The level of generalisation is in direct relation to the required resolution (level of detail) of the documentation, and the amount of interpretations and assumptions are in direct correlation with authenticity.

3.3 Conceptualised authenticity in archaeological documentation

In the case of the Skelhøj and Alken Enge excavations, the realisation of authenticity as a concept and tool in the excavation practice happened gradually and as an iterative process, reflecting technological developments since the turn of the millennium.

First of all, an evaluative authenticity-concept was implemented at the lowest level of the documentation ladder; in fact, authenticity was printed on context and find sheets in order to allow for an assessment of the observation/interpretation dichotomy. This gave the archaeologist the incentive to evaluate the documentation quality at a very early stage in the process, and impose the reflexive question: "how certain am I?" and "how well does this/my documentation reflect reality?"

Secondly, concepts of documentation units, documentation events and data collections were introduced to address the derivative nature of digital data, and record the historic dimension of the documentation process (Jensen 2012). This way, para and meta-data are explicitly contained within the documentation, and it is known how interpretations and representations evolve over time, as new data and new knowledge become available. Authenticity of the documentation has nothing to do with what is original, but simply how what we have now, the visual representation, relates to what was in the past; knowing that everything is derived. The combined parameters are what help ascertain the authenticity of the documentation, and becomes part of the hermeneutics of the documentation process, where the interpretation is not exclusively an end product of the documentation.

Thirdly, 3D models were increasingly used to visualise the spatial hypotheses of the ongoing excavation.

3.3.1 3D models and spatial hypotheses

Far from being limited to archaeology, it is easy to see how the 3D paradigm is currently trending in countless branches of computing. In particular, archaeology's most beloved tools: Geographic Information Systems (GIS) and Computer Aided Design (CAD) are merging and evolving into doing things which used to be limited to dedicated 3D software (Wheatley & Gillings 2002, Breunig, M. & Zlatanova,

S. 2011). Consequently, this also means dealing with different levels of abstractions, ranging from the reality-proximate and photorealistic via the delineative and generalised to the artistic and stylised representation.

In addition, 3D representation supports the combination of the observed with interpretation, following a more 3-dimensional reasoning, where we may apply 3D documentation as a tool for continuous monitoring and evaluation of an excavation and its results. Just like the general use of models to form hypotheses, it is possible to use 3D models as spatial hypotheses of an ongoing excavation. This allows us to visually realise or spatially conceptualise our hypothesis as a virtual reconstruction and to combine it with our observational data. The inherent issues of using photorealistic and high quality hypothetical visualisations as part of the documentation, and discerning which is which and accounting for level of certainty, was already touched upon more than 20 years ago by Eiteljorg and others (Eiteljorg 1998, 2000, Eiteljorg & Limp 2008). One of the main concerns was that visualisation tools are rarely capable of displaying uncertainty or fuzzy data, or levels of probability when it comes to reconstructions (Eiteljorg 2000, Miller & Richards 1995). "As disseminators of information to a data-naïve public, we must find techniques for displaying areas of fudged data within our models, and attempt to educate people in the skills of visual data analysis: an awareness of scale, an understanding of the fact that lines on maps often represent fuzzy boundaries, and a perception of the limitations inherent in our data" (Miller & Richards 1995:21). One such way of displaying uncertainty is by the use of colour, texture or opacity (fig. 3.3). This, however, trails back to the issues of relying on prior knowledge or an individual's intuitive ability to read and understand such visual information.

Additionally, there is a whole array of visual elements, which may not rely solely on archaeological evidence, and where the level of certainty is highly questionable. These may include, for example, written sources like Beowulf, which describes the appearance of the great hall building, ethnographic analogies, as well as the inherent assumptions governed by current trends and social/political circumstances. This is however part of a literary and societal discussion, rather than one of visual archaeological representation.

The concerns about scientific certainty in visualisations, among other, have led to the ratification of London Charter for the Computer-Based Visualisation of Cultural Heritage (Hermon, Sugimoto & Mara 2007, Denard 2012) – see Hermon & Niccolucci chapter 3. The London Charter highlights the major pitfalls of navigating the border zone between research hypotheses and public dissemination, but also hints at practices for combining reality data with model data. In this case, evaluating the level of authenticity, or uncertainty, is paramount to express the quality of excavation documentation, but as previously stated, authenticity may

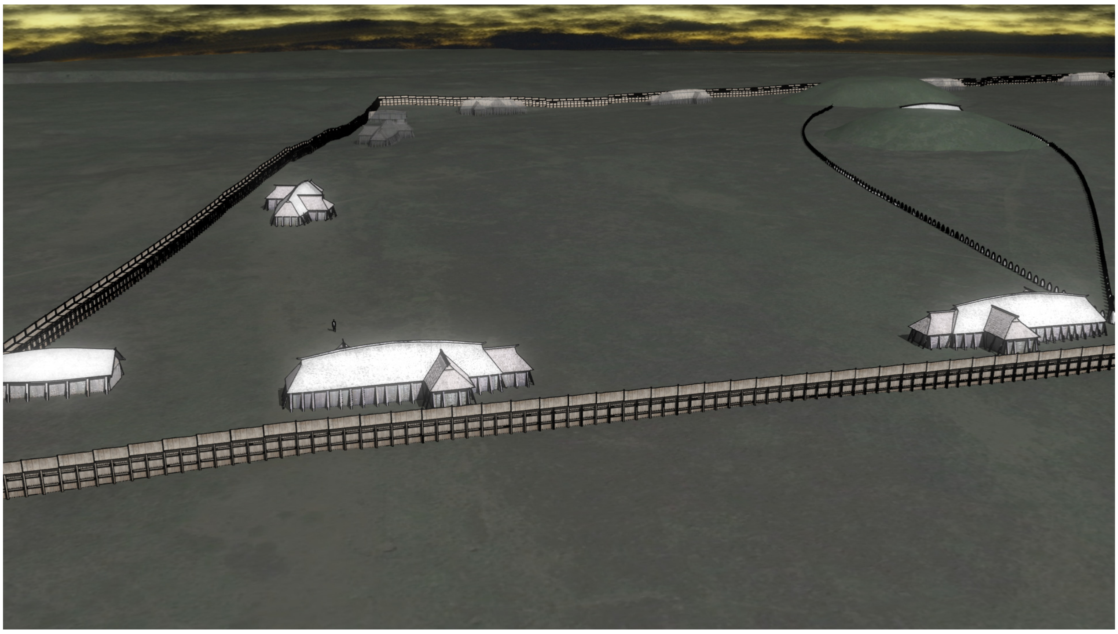

Figure 3.3: The Jelling Complex visualised as 3D animation for the VIKING exhibition at the Danish National Museum. The style is non-photorealistic, and levels of uncertainty or hypothesis are indicated by varying transparency of elements.

arguably also be integrated as a measurement tool that allows for evaluation of the empirical data and the excavation process.

3.3.2 The Viking Age royal complex in Jelling

As with Alken Enge, the excavations of the Viking Age royal monument complex in Jelling were to a very large extend based on digital photogrammetric documentation (Jessen et al. 2011, Holst et al. 2013). The 2010 campaign was targeted upon the large palisade structure, which encloses the mounds and the church, as well as the north-eastern quadrant (fig. 3.4).

The excavations revealed postholes belonging to buildings, which in their pattern strongly resembled the architecture from known Viking Age houses, usually assigned to King Harald Bluetooth and the circular fortresses at Trelleborg, Fyrkat and Aggersborg (Holst et al. 2013, Jessen 2015, Roesdahl et al. 2014). In this case, it is of course important to note, that prehistoric architecture in Northern Europe is very seldom a matter of filling in missing pieces of a ruin of known design like Classical and Romanesque architecture (Miller & Richards 1995, Huggett & Guo-Yuan 2000). We are talking about the excavation of sub-surface ephemeral features associated with organic evidence of postholes with very little else evidence. This is a factor which should somehow accompany any visualisation of such features.

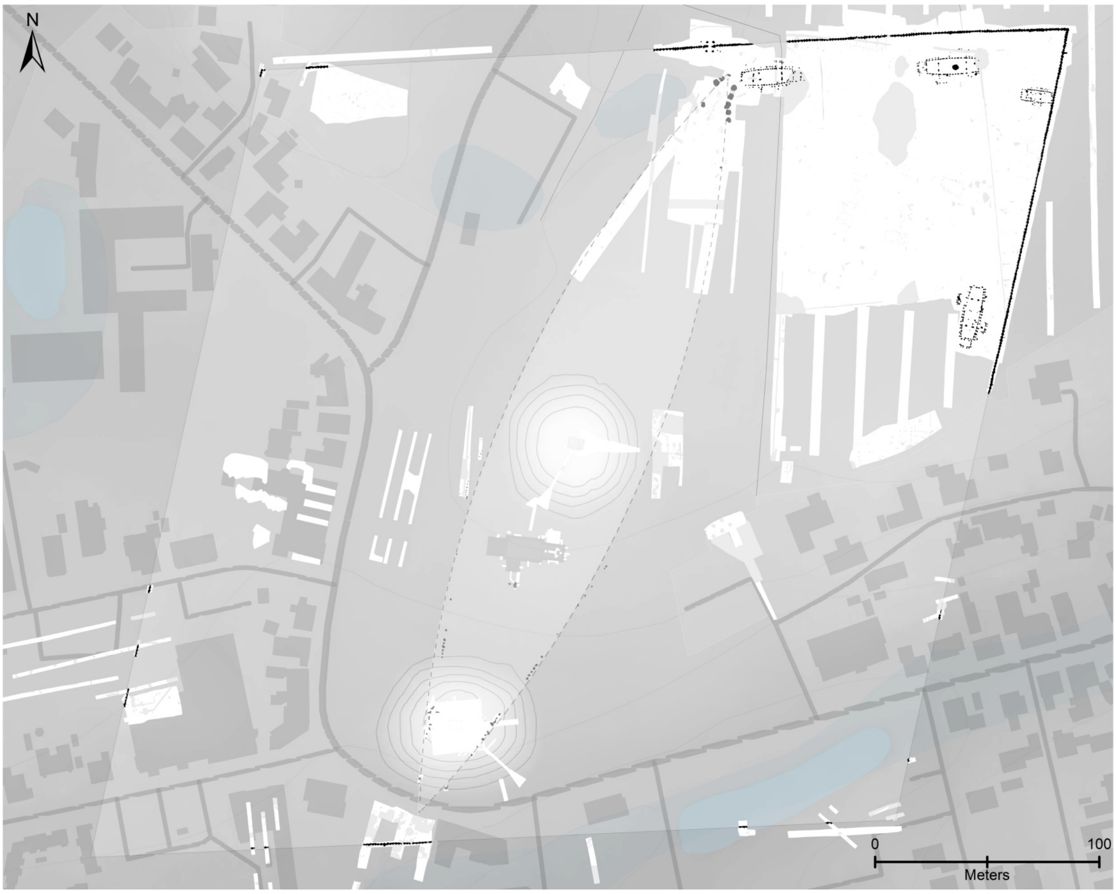

Figure 3.4: The Jelling Complex: A central complex with a church and two burial mounds, rune stones and stone ship setting. A palisade surrounds the monuments and buildings are placed along the inside at fixed intervals and orientation. Excavated areas shown in white.

Given that the houses at the circular fortresses tend to adhere to very strict geometric rules for placement, scale and orientation, meant that this was something which could be easily visualised and used to generate a working hypothesis of where to look for more houses, and estimate their architectural appearance – if indeed the similarities were substantiated. Key features of the Trelleborg-type houses are the unique entranceways and the double row of wall posts, presently interpreted as a combined wall and external supporting structure, following cruck construction. Neither the function of the external posts nor the entryways were initially identified by the early excavations of Trelleborg in the 1930s and 40s, but later excavations allowed archaeologists to reinterpret and physically reconstruct houses using these hypotheses (Schmidt 1981, Schmidt 1985, Olsen & Schmidt 1977) (fig. 3.5). This is itself an excellent example of how reconstructions, as well as archaeology as a whole, are a product of time and society (Trigger 1989), as

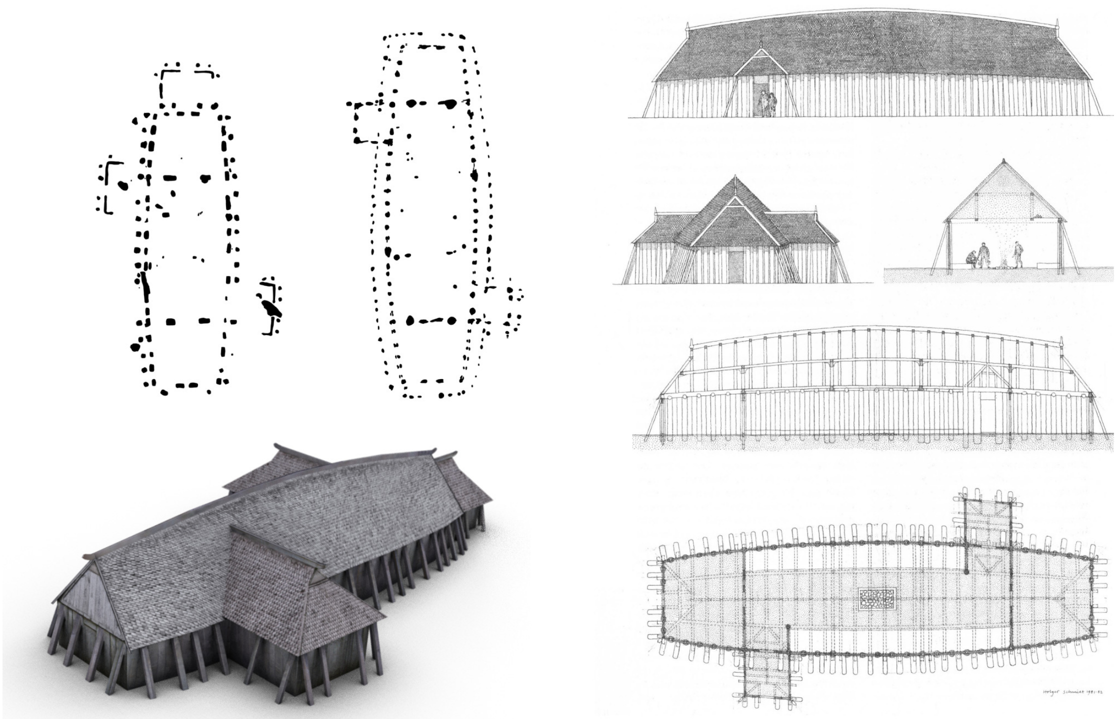

Figure 3.5: Plan drawings of postholes show the architectural similarities between a Jelling House on the left and a Fyrkat House on the right (Olsen 1977). Holger Schmidt's architectural drawings for the Fyrkat reconstruction are on the far right (Schmidt 1985).

the first reconstruction shows Roman-derived traits, know from porticoes around Roman villas and Romano-Celtic temples, compared to the later, more Germanic reconstruction with cleaner lines.

By almost direct comparison, the excavations at Cowdery's Down (Millett & James 1983) also deal with the identification and interpretation of slanting posts, and quite interestingly present not just one, but several alternative reconstructions based on the same archaeological evidence.

The initial excavations in Jelling, revealed one house with an entranceway on one side. It was however known from the reconstructions of Trelleborg-type houses at Fyrkat that the entranceways are placed on both sides, and displaced to either end (fig. 3.6). Combined with the observed systematic mirroring of the house orientation in the fortresses, this helped to guide the excavation into where to look for more entranceways, among the otherwise poorly preserved postholes. In addition, the Jelling houses turned out to have a very unique feature, as the gable ends would have an extension in either end. The Jelling-house, however, still adhered to the strict geometry and rules of mirroring and symmetry. The natural response was to try to 3D visualise this special structural feature on the basis of the architecture of the physical reconstruction at Fyrkat (Schmidt 1985) and apply it as a working spatial hypothesis for the excavation.

The visualisations were done in a combination of software: Agisoft Photoscan, ESRI ArcMap and ArcScene and 3D Studio Max. Acknowledging that archaeological interpretation is a dynamic and iterative process, different snapshots or documentation events account for the thought processes and expectations of the archaeological source material. This way, when these snapshots were made, by whom and based on what criteria, became the basis for evaluating the authenticity of the development of the spatial models, and the rationale for replacing one model with another revised model. The experiences gained in Jelling demonstrate how abstractions shape the basis for the archaeological process, and how 3D visualisation functions as a tool of reflection – combining what we know with what we expect.

The excavations at Jelling, and not least the intensified use of 3D models as spatial hypotheses, exposed the need for a framework to manage the iteration of interpretations. By including an evaluation of authenticity at all levels of the documentation pipeline, the system should be able to fill in the void of meta- and para-data, left by the break-down of the clear distinction between observation and interpretation, itself caused by the introduction of photorealistic 3D representations.

The evaluative process of the empirical data collected would generally follow a predetermined chain of events:

Figure 3.6: Photos of the reconstructed houses at Trelleborg (top) and Fyrkat (bottom). Photo: Anne Pedersen (top), Peter Jensen (bottom).

1. An opening strategy of excavation methodology and definition of Data Collections (Jensen 2012). The Data Collections were used as constructs, which served to collect all related primary data within well-defined physical boundaries. I.e. all descriptions, photos and measurements within a given area, which would tentatively be used to synthesize an illustration. In practice, each trench would act as a Data Collection.

2. Each consecutive Documentation Event would refer to a Data Collection in a one-to-many relationship, and provide primary data as well as derived data. Authenticity would be assessed through aggregated para- and meta-data.

3. Following a Documentation Event, results would be re-interpreted and synthesised into a separate Documentation Event containing a spatial hypothesis: GIS-plan or 3D model (see fig. 3.7). In this case, authenticity was expressed as levels of certainty and evaluated through the use of colour-coded visual elements.

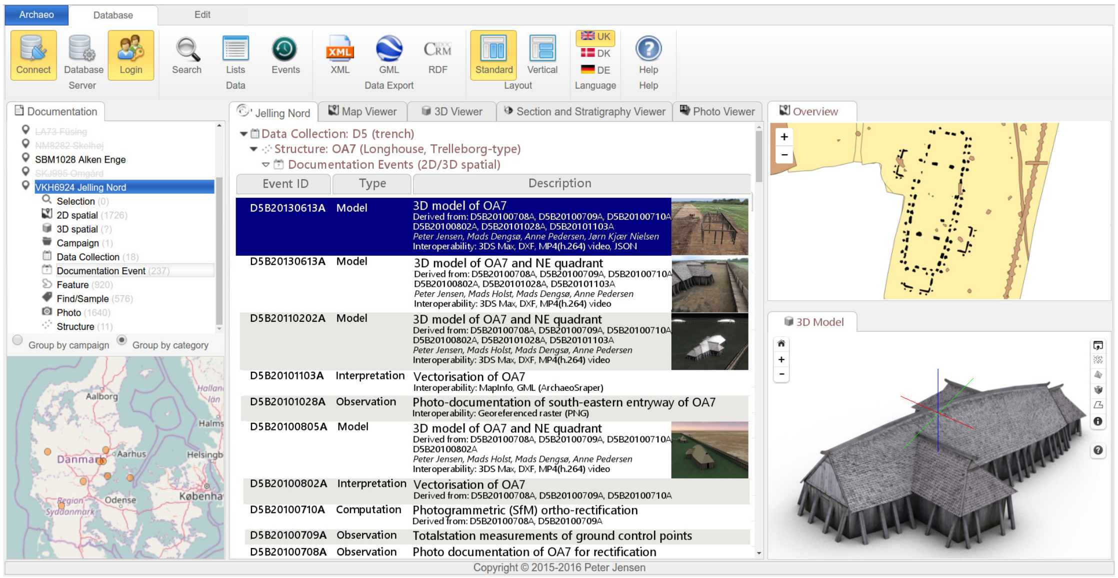

Figure 3.7: Screenshot of the Archaeo online database, currently under development. Displaying the chain of Documentation Events and iterations of spatial hypotheses while excavating the house OA7 in Jelling.

Each element would refer to back to the Documentation Event from which the interpretation derived.

4. The excavation strategy is reassessed and retargeted according to the revised hypothesis defined by the last Documentation Event. New Data Collections are defined, or new Documentation Events take place within existing Data Collections, such as documentation at a deeper level.

Finally, we should consider whether we need to quantify levels of authenticity, to tie our documentation to standards of processual archaeology, or if we should focus more on the separation of research vs. dissemination or hypothesis vs. fact in 3D visualisation to accommodate a different type of audience.

3.3.3 Unintended consequences; Research tool or public dissemination?

Visual models have a tendency to cement an interpretation as fact, rather than fiction or hypothesis, and even with proper precautions and disclaimers they easily evolve into a "truth", recognised as such by non-professionals. As already noted, this is also one of the main motivations behind the London Charter (Hermon, Sugimoto & Mara 2007, Denard 2012). This happens as archaeological research flows into public dissemination, where 3D graphics provide a marvellous tool to convey a story about the past. The use of models or reconstructions to convey a story, or even serve as experiments to test a hypothesis is nothing new, as already illustrated by the example of the physical reconstruction attempts of Viking

Age Trelleborg houses in Denmark by Holger Schmidt (Schmidt 1981). These reconstructions have, however, become representative of how the houses looked, even though we actually had two very different reconstruction attempts and therefore two conflicting architectural hypotheses. Paradoxically, this is the whole idea behind hypotheses or experiments; we learn from them and adapt our theories, which in this case, and in combination with subsequent research, has led to other or better interpretations of the architectural characteristics of the Trelleborg-type houses (Schmidt 1985, Jessen et al. 2011, Holst et al. 2013, Jessen 2013, Jessen et al. 2014, Jessen 2015). The challenge is how we convey this to the public in terms of authenticity. Compared to previous generations, what has changed is that 3D models and visualisations now reach the public much faster and through different media, and potentially without the necessary scientific discussion. Computer models tend to carry more authority than paper images and "Large audiences are being exposed to visualisations in circumstances, where the pictures or animations are divorced from the academic discussion..." (Miller & Richards 1995:20).

When the excavations at Jelling encountered postholes of Viking Age buildings, which in their outline showed similar characteristics, the natural thing was to use the same architectural idea in 3D models, which helped the archaeologists get an impression of the site as it was excavated. Inadvertently, due to the high demand of something to show the public, these models were shared at a very early stage, and soon ended up in newspapers, information posters and even went into the new museum exhibitions. Fortunately, the Visitor and Experience Centre at Kongernes Jelling - Home of the Viking Kings, were very aware of the academic discussions and the reservations about visualising ongoing research. They often brought in the archaeological team to re-evaluate the architectural basis for the interpretations in the light of the new excavations and archaeological evidence. It, however, still became a struggle between scientific integrity and the public demand for visualisations.

One key feature of the "old" reconstructed houses were the hipped roofs which were part of Schmidt's original reconstruction at Fyrkat. The process meant that this feature was inherited by the visualisations of the Jelling houses, despite the fact that current interpretations of the postholes suggest gabled roofs were more likely. Stepping into a brand new exhibition and seeing visualisations based on a, now outdated, excavation hypothesis naturally causes concerns that an inauthentic or unsubstantiated account of the past is being conveyed to the public (fig. 3.8). The museum has addressed these challenges by actively introducing several interpretations of different architectural elements. An example of this is the Viking Age palisade, which went through several iterations in the archaeological spatial hypotheses. For 2017 a physical reconstruction of a section of the palisade is planned for the museum gardens, which will include several elements from the

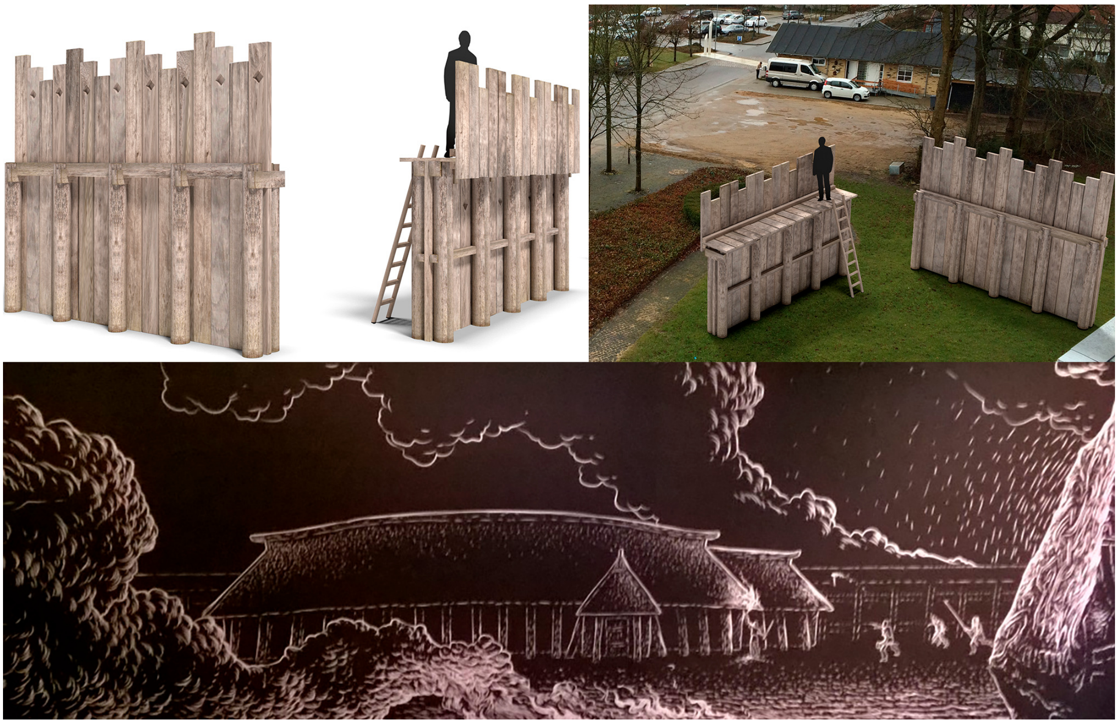

Figure 3.8: 3D model of the planned physical palisade reconstruction (top left and right). Photo: Peter Jensen. The exhibition wall backdrop at the Visitor and Experience Centre at Kongernes Jelling - Home of the Viking Kings, showing an artistic rendering of an outdated spatial hypothesis (bottom). Painting: Sebastian Bausdorph, photo: Adam Bak, Kongernes Jelling.

various interpretations regarding, height, paint, carvings and general architecture (fig. 3.8).

Another example is the recent discovery of the Viking Age ring fortress Borgring, south of Copenhagen (Holm & Sindbæk 2014). Even though the preliminary excavations only revealed ramparts, gates and ditches, it was expected that it would be similar to the other Viking Age fortresses, in having 16 buildings inside (fig. 3.9). Current excavations so far have however not found any evidence of buildings, which strongly conflicts with the 3D model, which was made to illustrate a hypothesis about what kind of feature had been discovered to the public (Persson 2016).

As the producer of these models, one realises first-hand the importance of the London Charter (Denard 2009, Hermon, Sugimoto & Mara 2007, Denard 2012) and the challenges of navigating the grey zone between archaeological documentation, hypotheses and public dissemination.

Despite all possible disclaimers, there is a demand from the public and exhibitions to visualise archaeology, not just as postholes, but to reveal what the archaeologists are thinking and to offer an informed opinion of what features might have looked like. One instrument to accommodate both is to refrain from photo-realistic models altogether (fig. 3.3). Yet is it safe to assume that the audience most likely already realise it is a model, but trust the authority when we present a model or claim? We should not underestimate the capacity of the audience to deal with uncertainty. What really matters is the ability to account for or justify the visualisation, and in doing so, facilitate access to raw data as well.

The London Charter clearly states: “Sufficient information should be documented and disseminated to allow computer-based visualisation methods and outcomes to be understood and evaluated in relation to the contexts and purposes for which they are deployed” and “Documentation of the evaluative, analytical, deductive, interpretative and creative decisions made in the course of computer-based visualisation should be disseminated in such a way that the relationship between research sources, implicit knowledge, explicit reasoning, and visualisation-based outcomes can be understood” (Denard 2009:8). This is not an easy task to accomplish, but evidently transparency of what the model is based on is what defines its authenticity. As Eiteljorg (1998) put it: ”If we only present a simplified and sanitized view of the past, especially one that seems real and is visually compelling, we will have failed those who want truly to understand, both as scholars and as users of the technology”.

On the other hand, the chances are that we are overly concerned with muddling the border between reality and model. Arguably many post-processual archaeologists could be accused of being overly obsessed with measuring and recording the past in as detailed a fashion as possible – perhaps forgetting that “not everyone even wants authentic archaeologies - whether scientific or not - and understand what this fact means for professionals who work in the public sphere” (Lovata 2007:21). While the use of 3D-“replica”, -models or -visualisations in archaeology is susceptible to being criticised for overstepping the bounds of scientific ethics, other disciplines do not appear to have the same reservations. Take, for example, the visualisations which accompany space exploration by organisations like NASA and ESA which also have public dissemination as a top priority. The use of computer-generated imagery has grown substantially in this field during the last 20 years. In order to accommodate the audience, data from deep space, which like archaeological 3D data is based on sensor-input and calculations, is often post-processed to an extent where it has very little to do with reality, and rarely do the authors bother to write “an artist’s impression”, when it surely is. In these disciplines, public dissemination and “raw” research data appear very disassociated, which is in striking contrast to how we currently pursue archaeology, where public engagement and immediate publication of research data tend to be vital. On the other hand, some would argue that archaeology is hardly “rocket science”.

3.4 Conclusion

Does authenticity qualify as a conceptualisation of documentation quality in a world of reality-proximate, photorealistic and geometrically accurate digital representations and visualisations? At first hand, it might appear somewhat ambiguous. In particular, because the most common use of authenticity in archaeology refers to individual objects and artefacts of the past, rather than the replication of an event of the (near) present, which the photogrammetric field documentation represents. On the other hand, what such conceptualisation portrays is a very conventional notion of authenticity; as one that is achievable through its representation of reality. But why do we not just call it documentation quality? This all points back to the dichotomies of archaeological science, and mainly the dichotomy of observational reproduction and interpretational reconstruction. Whereas the first might very well be addressed through a quantitative evaluation of the derivative nature of data processing through the recording of para- and meta-data, it does not account for the interpretive and reflexive element of utilising 3D models as representations, which are more or less reliant on the subjectivities of archaeologists. Furthermore, the concept of quality does not describe the spatial hypotheses which the latter represents, and the varying certainty of the reconstructed elements within.

Authenticity remains, in part, a subjective notion concerning the trustworthiness of a visual representation, but the experiences from the cases presented in this chapter also demonstrate how authenticity may be integrated as a concept and a tool in a spatial database. The immediate accessibility and transparency of data is a key issue, and the documentation events in the database reflect the iteration of spatial hypotheses, facilitating a less deterministic approach to archaeological visualisations in documentation as well as dissemination.

What remains are the unintended consequences of multiple versions of interpretations reaching the public audience. But as much as technology is to blame for rapid distribution of tentative reconstructions, it may also hold the key to solving the issue. As more and more museums apply digital and interactive elements to exhibitions, it is only natural to make use of less static exhibitions, which traditionally could be on display for years if not decades. An interactive 3D model in an exhibition is easily and inexpensively replaced with an updated hypothesis, while returning visitors increasingly expect exhibitions to reflect the latest research. In turn, the public may grow accustomed to this kind beta-exhibitions, which are always improving – and in the process become more aware of the iterative process and nature of archaeological interpretation.


30. MAJ. 2016 KL. 09.03

I dag indvier dronningen unik genfunden vikingeborg

Majestæten kaster i dag glans over åbningen af et unikt cirkelformet militært forsvarsanlæg fra vikingetiden.

Figure 3.9: DR News online (www.dr.dk) depicting the Borgring visualisation next to queen Margrethe II at the day she inaugurated the new excavations.

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Semantically enhanced 3D: A web-based platform for spatial integration of excavation documentation at Alken Enge, Denmark

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Abstract: The photorealistic and geometrically accurate 3-dimensional representation of excavations, provided by image-based modelling, has the potential to transform the process of excavation documentation, making it easier to share observations with other researchers. Paradoxically, however, the spatial representation lacks the ability to convey archaeological interpretations. By example of excavations in Alken Enge, Denmark, this paper explores how a web-based 3D platform is able to facilitate the collaborative exchange of 3D excavation content and how the integration of spatial and attribute data into one common event-based data model may be advantageous. This includes enhancing the semantic value of field-recorded 3D models by segmenting the geometry using various techniques, such as 3D projections and machine learning. Accordingly, the paper demonstrates a framework for interactive 3D models, which includes attributed classification, based on segmented 3D content correlated with traditional raster, vector and textual data, delivering a spatially integrated platform for collaborative research.

4.1 Introduction

The promise of 3D photogrammetric field recording is currently out of alignment with archaeological practice. The photorealistic and geometrically accurate representation of excavations, provided by technologies such as Structure from Motion (SfM), has the potential to transform the process of post-excavation interpretation, making it easier to share observations with other researchers. Paradoxically, however, the spatial representation lacks the ability to convey archaeological interpretations, as existing solutions usually only provide surface geometry and texture. The advent of HTML5 and WebGL means that browsers can interactively render and manipulate 3D content, leading to a distinctly different approach to data management. The potential of online frameworks changes the file-based paradigm, which for decades was the premise for digital field recording. Not only are thousands of desktop databases, spreadsheets and GIS tables a legacy we are forced to deal with; but more files are being produced every day. In addition, the increase of new file formats related to the spatial management of complex data such as 3D-data, challenges not only data archival procedures, but also affects the premise for collaboration. Rather than enforcing new standards for 3D content, this paper seeks to focus on the development of tools and frameworks for data management and exchange of 3D content. This includes the scientific augmentation of 3D representations through supervised segmentation and classification and harvesting of file-based field documentation.

By example of the excavations at Alken Enge, Denmark, this paper discusses how a web-based 3D platform is able to facilitate the collaborative exchange of 3D excavation content almost instantaneously and how such a platform, based on a philosophy of integrating all spatial and attribute data into one common event-based data model, may be advantageous. Focusing particularly on how we may use custom algorithms to enhance the semantic value of field-recorded 3D models by segmenting the geometry. Accordingly, the paper demonstrates a framework for interactive 3D models, which includes attributed classification, based on segmented 3D content correlated with traditional raster, vector and textual data, delivering a spatially integrated platform for collaborative research.

4.2 The photogrammetric toolbox of digital archaeology - going 3D

The growth of digital archaeology has introduced photogrammetry as one of the most promising additions to the archaeological toolbox, and it is evolving into one of many standard tools for archaeological field recording. In particular, the use of SfM is considered an affordable and efficient way of generating highly detailed, photo-realistic and geometrically accurate 3D models for excavation documentation (Huggett & Guo-Yuan 2000; Pollefeys et al. 2001; Katsianis et al. 2008; Ducke, Score & Reeves 2011; Dellepiane et al. 2013; De Reu et al. 2013, 2014; Dell'Unto 2014; Powlesland 2014; Forte 2014; Forte et al. 2015; Berggren et al.

2015; Dell'Unto 2016). Supplemented by laser scanning and precise measurements by differential GPS and total station with integrated GIS or CAD-solutions, it has the potential to provide everything archaeologists need in terms of accuracy and speed of acquisition. Nevertheless, it is frequently debated what exactly it is that photogrammetry, and 3D-recording in particular, offers in terms of revolutionising excavation recording or even how it contributes to the creation of new knowledge compared to more traditional recording methods (Hodder 2000; Losier, Pouliot & Fortin 2007; Berggren et al. 2015; Dell'Unto 2016; Forte 2014). Photographs as media - and digital photography in particular (Morgan 2014; Bateman 2008, 2006; Morgan 2016; Morgan & Wright 2018) - are comparable to the 2D-representations we know from traditional paper drawings, but inherently provide a more precise portrayal of the observed situation. Photographic evidence is, however, limited in its ability to carry the semantic annotations and classifications, which are used to convey the archaeological interpretation. Subsequently, recurrent use of photos and digital photogrammetry for field recording becomes a determining factor for the way archaeological documentation is used and managed. For instance, a fundamental facet is the acceptance that all digital documentation tends to be derived from something else. Consequently, rectified, processed or digitized photos are something fundamentally different compared to a paper drawing – they are snapshots of the observed reality, yet require a level of manipulation in order to be useable for documentation. The clear advantage of a photo-realistic representation of an excavation is the way it strengthens the unambiguous distinction between observation and interpretation. This in turn requires that we are able to track and account for changes to data, and special attention is required regarding the management of digital excavation data. In a world of digital archaeology, photographic evidence may be considered one of the most essential assets for collaborative efforts. In particular, this is the case if we focus on the ability to share and discuss archaeological observations, rather than accepting derived interpretative delineation, which is the norm for archaeological GIS or CAD representations. It does, however, lead to a question of how photorealistic 3D-representations may improve or affect the collaborative preconditions, provided that a suitable framework for the exchange of data exists.

4.2.1 Archaeological visualisation

Despite a series of 2D and 3D archaeological applications in the early 1990s, such as Hindsite (Alvey 1989, 1993), the interactive and collaborative potential of 3D visualisation were not thoroughly addressed before the early 2000s, by which time technological developments had introduced 3D representations into archaeological fieldwork. In 2004, the VITA system (Benko, Ishak & Feiner 2003) demonstrated a multi-user, off-site visualisation system for archaeological excavations. This was followed by an increasing number of visualisation as well as immersive and virtual reality applications (Bobowski, Walczak & Stawniak 1991; Mills & Baker 2009). Several of these tools had great potential, but were generally lacking in their ability to combine visualisation capabilities with a solid database management system for spatial and stratigraphic data.

In the last decade, two diverging trends have developed, which may be traced back to the methods by which excavation data is managed and produced. On the one hand there has been a focus on the possibilities of online infrastructures and the interoperability provided by the semantic web (May, Binding & Tudhope 2008; Binding, May & Tudhope 2008; May et al. 2012), while there has been a parallel focus on off-line, file-based desktop applications (Dell'Unto 2016; Katsianis et al. 2008). The latter are closely linked to the extensive use of GIS or CAD in the archaeological pipeline. Both trends, however, testify to a departure from basic dissemination of cleaned and synthesized data, towards an aim of more extensive on-site collaboration and metadata management.

4.2.2 Desktop 3D GIS

Geographic Information Systems are traditionally and inherently 2-dimensional, and use various geographic projections to represent and visualise mapping to a sphere (Wheatley & Gillings 2002; Conolly & Lake 2006). Any 3D recorded or modelled content is traditionally represented in GIS using what is characterised as 2.5D or quasi-3D to simulate the appearance of being three-dimensional. 2.5D representations use, for instance, extrusion of Digital Elevation Models (DEM) or interpolation of elevation data to represent facets in a triangulated irregular network (TIN). In these cases, 3D-information is not an independent variable, and representations are subject to the same premise of 2D-projection onto a mathematical description of the globe. Having a true 3D GIS-solution, however, provides for a non-predetermined visualisation, potentially making the excavation process more reflexive and contextual (Berggren et al. 2015; Dell'Unto 2016, 309). This allows researchers to engage with field recording and spatial representations in novel ways and readdress the archaeological record with new research questions. In practice, several archaeological projects now make use of the recent developments of 3D capabilities in ESRI's ArcGIS - and in particular ArcScene desktop applications. With 3D Analyst extensions it is possible to directly import, visualise and analyse 3D surface models in combination with more traditional vector and raster GIS datasets (Dell'Unto 2016, 311). This use of 3D GIS in support of archaeological interpretation has been employed at major excavations projects such as Çatalhöyük (Forte 2014; Forte et al. 2015; Berggren et al. 2015; Hodder 2000; Dell'Unto 2016), while its analytical capabilities for visibility analysis has been explored in ancient Pompeian houses (Landeschi et al. 2016). Other options are becoming available as open source projects such as QGIS and GRASS GIS are also integrating true 3D capabilities, for instance through the use of voxel modelling (Lieberwirth 2008; Merlo 2016; Orengo 2013). Common to these solutions is the possibility to merge and visualise different data types. Instead of vectorising using 2-dimensional surfaces, which is common practise when employing georeferenced drawings or orthophotos, it is possible to draw in 3D, using the 3D model as a canvas to which the delineated polygons will conform (Kimball 2014; Dell'Unto 2016). Without doubt, this affects the archaeological preconditions for collaborative interpretation by integrating traditional and innovative 3D practices, while increasing accuracy and realism of documentation; delivering a richer and more complete record.

4.2.3 Online interactive 3D

The inherent limitations of commercial desktop GIS, which also affects its collaborative potential, is the lack of interoperability, due to the need to install proprietary and expensive software. Recent advances in free open-source systems, such as QGIS with its database connectivity, geojson support, and Python API, offer high-level interoperability, while the introduction of industry standards as HTML5 and WebGL means that "being online" is profoundly affecting the preconditions for archaeological documentation, collaboration, dissemination and visualisation. This is perhaps most evident in the evolution of national sites and monuments databases, which were relatively early adopters in making data accessible for the public (Hansen 1992). Now it is usual not only to disseminate archaeological data online, but to include far more interactive and immersive access to data. Furthermore, the support by all major web-browsers for client-side scripting and hardware accelerated graphics, as well as cross-platform designs, means that complex spatial content is now available on devices ranging from smartphones to desktop computers. This is a technology which has already seen applications in other disciplines such as geology (Herzig et al. 2013) and palaeontology (Michaux et al. 2015), and has immense potential for archaeology.

The capabilities of 3D interactive visualisation, now being exploited by archaeological institutions to present artefacts and cultural heritage, make extensive use of the services provided by companies like Sketchfab (`https://sketchfab.com/museums`) (Means 2015). However, for archaeological use, such proprietary services are often limited in their data integration capabilities, due to their generalised application without the essential requirement for customisation of data integration. For such purposes, two archaeological projects stand out:

MayaArch3D (`http://www.mayaarch3d.org`) is a web-based virtual research environment for documentation and analysis of complex archaeological sites, which integrates 3D models of cities, landscapes and objects with associated, geo-referenced archaeological data in a 2D/3D WebGIS (Agugiaro et al. 2011; Auer et al. 2014; Agugiaro 2014). It offers an innovative database and system architecture, which is one of the first examples of combining 3D models and traditional GIS online. Likewise, its vast analytical capabilities are commonly seen only in powerful desktop GIS solutions. The project focuses on the eighth-century Mayan Kingdom, and makes extensive use of WebGL and JavaScript for the visualisation of 3D models while a PostgreSQL database with PostGIS extensions is used for storing both 2D geometry and 3D objects (Auer et al. 2014, 35). An interesting feature of the MayaArch3D is its capabilities for storage and management of segmented models, given that a segmented model is a prerequisite for embedding semantic information. By effectively annotating and classifying individual parts of a 3D model, its potential as an information-carrier approaches that of the archaeological drawing, while retaining the additional detail and realism gained from photogrammetric recording. The segmentation process is done manually by Maya researchers using a hierarchical system of semantic object classes and several levels of subclasses, and allows users to access elements of 3D models as individual features, rather than one continuous 3D surface, which we have otherwise become accustomed to.

Another project, which is proving its value by enabling web-based 3D capabilities and data repository integration, is the ADS 3D viewer (Galeazzi 2014; Galeazzi et al. 2016). The viewer is actually two separate instances; an Object Level 3D Viewer and a Stratigraphy 3D Viewer, each seeking to accommodate different user needs. The stratigraphy viewer allows the exploration of the sequence of layers in an archaeological stratigraphical representation, while the Object Viewer mimics much of the functionality of more general 3D implementations.

The ADS 3D Viewer is built on top of the Archaeology Data Service's data repository, and therefore demonstrates a strong link between visualisation and data. The development represents a customisation of the 3D Heritage Online Presenter 3DHOP (Potenziani et al. 2015), taking advantage of its high level of detail compared to other solutions such as Unity or Adobe 3D. It also uses the Nexus open source library for multi-resolution and progressive loading, which is advantageous for transferring large quantities of mesh-data for client-side/browser 3D rendering.

Apart from the common navigation tools for rotating and exploring 3D models, the 3DHOP Viewer also offers tools for interactive illumination, distance measurements and sectioning, providing valuable tools for collaborative exploration of data. The integration with the ADS Archive is achieved through 3D hotspots, which are clickable points in 3D space that allow annotation and links to relevant data records in the vast archaeological repository and grey literature at the ADS.

At present, a distinct difference exists between such online viewers, which are semantically linked to synthesized and harmonised archival data, and the requirements for an online infrastructure for visualising ongoing field work documentation. Such data tend to much more ad-hoc, derived and intermediate. The common denominator is obviously the visual component, but for fieldwork it is inevitably much more closely linked to the documentation pipeline, and in the case of 3D photogrammetric documentation – the Structure from Motion workflow.

4.3 Alken Enge - a Structure from Motion Workflow

In 2012, Aarhus University in collaboration with Museum Skanderborg and Moesgaard Museum reopened the archaeological investigations of the Alken Enge wetlands in central Jutland (Hertz and Holst 2015; Holst et al. 2018) Alken Enge constitutes an area of almost 40 ha situated at the outlet of the Illerup River into Lake Mossø. The Illerup River Valley is world-renowned for its weapon sacrifice, comprising more than 15.000 artefacts, mainly weapons, dated 200-500 AD (Ilkjær 2002). Like the Illerup River Valley, Alken Enge was investigated during the late 1950s by archaeologist Harald Andersen as drainage work had unearthed significant amounts of finds; but unlike the weapons and personal equipment of an Iron Age army found further upstream, the Alken Enge site produced more than a thousand scattered human bones. Radiometric dating places them prior to the weapon sacrifice; in the first half of the first century AD, yet the bones all point to young males, many of which had battle wounds, clearly pointing towards acts of war. The presence of post-battle bone trauma, as well as four human pelvic bones threaded on a branch has led to theories concerning human sacrifice and rituals in the aftermath of battle.

The very challenging excavation conditions were well known from the excavations in the 1950s and 60s (Andersen 1956); excavating bog peat to a depth of over 2 meters, and working below the water table of the neighbouring Lake Mossø. As with any wetland excavation, it required technical solutions for controlling the water level while maintaining the anaerobic and humid preservation conditions. Furthermore, the stratigraphy of the different geological and archaeological deposits was extraordinarily complex. Reviewing the traditional paper documentation of the 1950s created concern that such methods were not able to convey a sufficient level of detail. Despite being remarkably meticulous and precise, even across large distances, Harald Andersen's traditional recording did not fully account for the stratigraphic complexity and deposit sequence, nor did it clearly visualise the arrangement of human bones, scattered on the ancient lakebed. The paper documentation was generally limited to one or two plan drawings of each sector, with annotations of find numbers and levels of all bones and major pieces of timber (see fig. 4.1).

Having pioneered the development of digital photogrammetric documentation in Denmark in 2002 and 2003 at Skelhøj (Holst & Rasmussen 2013; Johansen 2003; Scollar 1998), followed by experiments with digital stereo photogrammetry for the creation of simple 3D models of complex data (TopCon Imagemaster), Unit of Archaeological IT and Aarhus University established a documentation pipeline and workflow, centred around the consistent use of photogrammetry based on

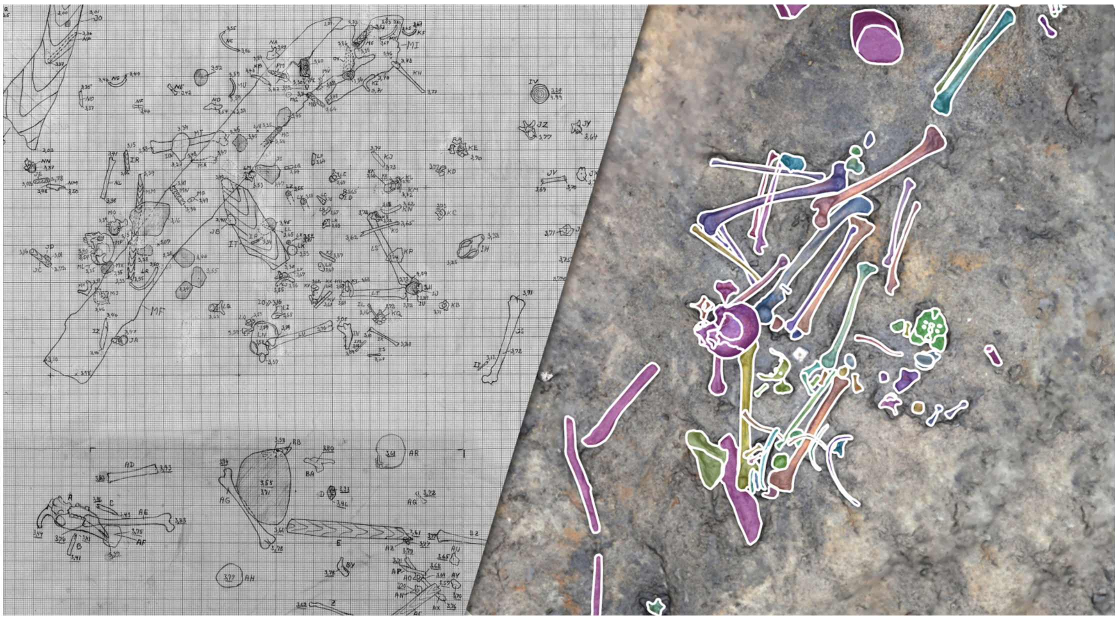

Figure 4.1: Excavation plans of Alken Enge from the early 1960s compared to modern SfM photogrammetric recording of the same site using ortho-rectification, georeferencing and vectorization.

SfM. This was in part inspired by the documentation and interpretation process at Çatalhöyük (Hodder 2000; Forte et al. 2015), while the introduction of SfM and the move to 3D was essential to accomplish digital photogrammetric recording under these circumstances. Traditional digital photogrammetry is limited to the geometric rectification of photos based on measured and georeferenced ground control points, which only works well on completely level surfaces. The situation in Alken Enge was far too complex and the large quantities of timber that had floated around in the prehistoric lake and river, and even in-situ standing wooden structures, would protrude any level surface and result in distinct perspective distortions or "Escher-effects" on all orthogonal representations (see fig. 4.2).

From the outset, a combination of VisualSFM (Wu 2016) and MeshLab was employed to create textured 3D-meshes, which were then projected through a top-down orthogonal viewport with the purpose of generating a true orthophoto that could be georeferenced in ArcGIS using measured ground control points. Later, this workflow was enhanced and simplified using Agisoft PhotoScan and its built-in processing capabilities for generating geometrically true orthophotos. It is important to acknowledge that the primary argument for adopting 3D documentation in this case was the precise generation of 2-dimensional, rectified orthophotos, which could be used as a more detailed substitute for traditional paper drawings. Meanwhile, the ambitions rapidly grew to an evident concern about how to manage 3D

Figure 4.2: A 2D-rectified excavation orthophoto, showing pronounced geometric distortions or "Escher-effects" of protruding wooden structures. The same problem visualised through first-generation Google Earth imagery (Google Maps 2010; Chris Silver Smith).

data – and not least – how to put it to proper use and harness its full potential. Fortunately, the photo documentation workflow was kept consistent throughout the successive excavation campaigns, which meant that new ideas and more advanced processing capabilities could be introduced progressively and retrospectively.

The complex stratigraphy (see fig. 4.3) did not encourage a single context approach (Harris 1989; Roskams 2001) as the hundreds of geological deposits and erosions, brought on by 2000 years of lake and river dynamics, were intertwined with organic material, branches and timber. Furthermore, the oxidation of the peat resulted in almost instantaneous discolouring, making it impractical to excavate only one context at a time. Instead, by relying on the observations made by Harald Andersen in the 1950s as well as test pits in 2008 and 2009, a documentation strategy was established, aimed at documenting predefined levels, which were determined by the prevalent hypotheses (see fig. 4.4).

4.3.1 Conceptualising a digital approach

One of the main challenges of applying digital excavation strategies is factoring in the human equation. Archaeologists are generally very fond of arranging field recording by way of numbers and lists, and it is an important part of manifesting how they think and work (Roskams 2001; Lucas 2011; Carver 2009; Carver, Gaydarska & Monton-Subias 2015). This way, every drawing, photo, sector, feature, context, stratigraphic unit or find are assigned unique numbers that assist in organising and relating the individual elements of field recording. In a digital approach, however, this makes proportionally less sense, as the amount and different types

Figure 4.3: Photomontage illustrating the difficult excavation documentation at Alken Enge and the complex stratigraphic sequence in the section profile.

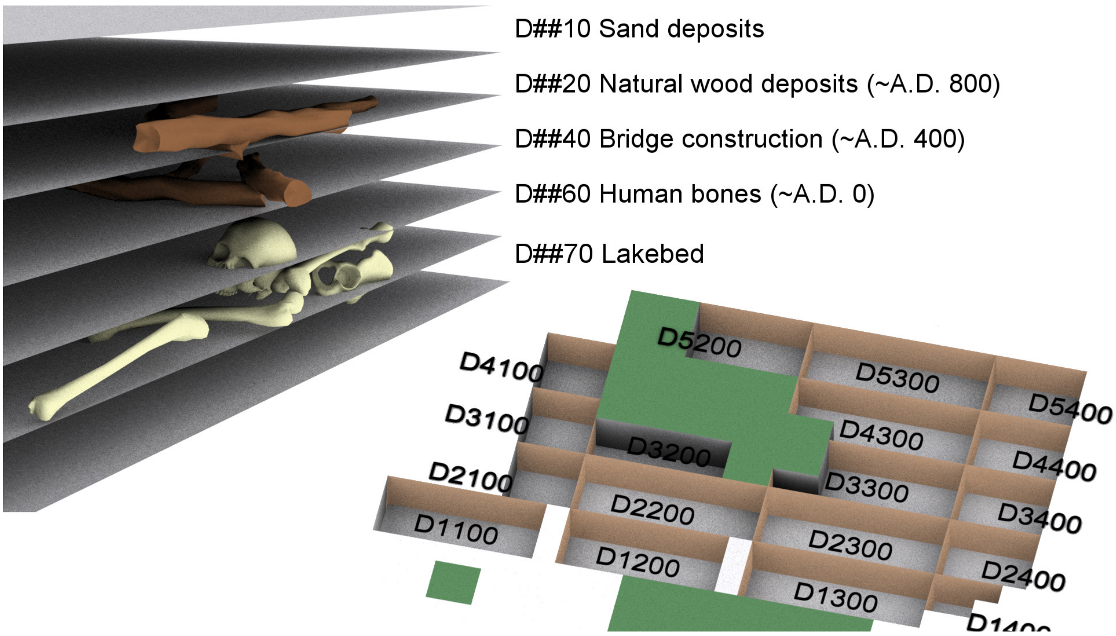

Figure 4.4: Predetermined stratigraphic levels of documentation and naming convention of Data Collections and Documentation Events.

of recorded data increase substantially; for instance the thousands of photos and control point measurements used for photogrammetry. Accordingly, a 3D model is something significantly different compared to a hand drawing; and is derived from a combination of many types of input. The immediate solution would be for the computer to keep track of numbering the documentation elements automatically. This procedure was evaluated during the test pits in Alken Enge in 2009, and resulted in a significant increase in human error. When employing an arbitrary number, human beings are much more likely to make mistakes, compared to when using a methodical naming convention. As a result, the digital approach at Alken Enge called for a naming convention of semantic numbering that would introduce a principle of spatial awareness at the level of human-computer interaction, while retaining a degree of machine-readability, which would allow for automated procedures for data processing. This is not unlike the aims of the KAP Recording System (Roosevelt et al. 2015), which seeks to provide a logical and internally consistent system of recording and managing spatial and aspatial information in a digital, 3D field recording pipeline. The KAP system uses a tripartite nested system of record identification, which includes area, spatial context, and sample IDs. At Alken Enge, concepts of Documentation Events and Data Collections were introduced in support of the collaborative efforts of many people working at the same place at the same time (see fig. 4.4). This also addressed the derivative nature of digital data, and recorded the historic dimension of the documentation process (Jensen 2012; Holst 2013). Para and meta-data were explicitly contained within the documentation, and it was explicitly articulated how interpretations and visual representations evolve over time, as new data and new knowledge become available (Jensen 2018).

A square meter grid covering the research area was extended from the old excavation areas, and partitioned into sectors of 8x4 meters, corresponding to where trenches could be placed. The naming-convention conceived, was based on a hierarchy of Data Collections and Documentation Events. Starting from the origin of the grid, every sector was considered a Data Collection with its own unique D-number. The first digit being the relative sector position in the north direction, while the second digit shows the sector position in the east direction. The predefined levels would add intervals of 10, leaving room for inserting intermediate documentation levels when necessary. For instance. D1060 would translate to the sector immediately east of the origin, at level 6, which would usually correspond to the bone deposits on the lakebed (fig. 4.4). This proved to be an intuitive way of relating to the precise individual sectors and stratigraphical levels of the excavation, and provided a vocabulary for efficient communication between archaeologists. Furthermore, it provided an immediate validation of the numbers, as it could usually be deduced as a description of the relative location, rather than an arbitrary number. Within each Data Collection one or more Documentation Events would take place. Documentation Events were designated by the creation date in the format B[YYYYMMDDI] with the prefix B and a suffix [I], meaning that the complete identifier of an event would be something like D1060B20130615A. These events would usually encompass the entire pipeline of the documentation process, ranging from photos, measurements, processing and vectorisation, as well as the written record of archaeological interpretation and description. The outcome was an efficient way of keeping related documentation material combined and accessible for processing. The different Data Collections would act as containers for different visualisation purposes and help users navigate the excavation both horizontally and vertically, and piece together minor documentation units to form coherent sections and plans; for instance one particular level or combination of sections. The individual sectors were excavated consecutively, providing main profile walls in an east-west direction at intervals of 4 meters, which could be correlated and allowed for hypothesis validation against the observed layers (see fig. 4.4).

At first glance, it may seem irrational to be concerned with numbers and the designation of elements in a world of computers and digital archaeology. More than anything, it is likely to be a testimony to a limited archaeological methodology in the scope of computer-human interface, and how distinctions are made between human- and computer generated data. Furthermore, what archaeologists assign numbers to, does not necessarily correspond to a physical or even spatial entity, which is why it is an extremely complex and sometimes arbitrary relationship to model. With semantic numbering, the inherent risk of human errors while assigning numbers is reduced as the assigned identifiers include a conceptual and spatial component. When errors eventually do happen, the consequence is nevertheless greater as "meaning" has been assigned as part of a unique number, and cannot easily be changed. However, if we are to interpret data, a vocabulary and designation of different elements are a fundamental requirement, and a necessity for collaborative discussions.

4.4 3D Segmentation and Annotation

As discussed above, the main motivation behind the early adaptation of 3D photogrammetric recording using either stereo photography and later SfM at Alken Enge, was the shortcomings of traditional photo rectification. Although flat surfaces are usually a core ideal of field archaeology, in reality it is virtually impossible to achieve, and the geometric distortions of having an uneven surface projected onto a 2D-plane are often considerable. Paradoxically, the target of flat surfaces contradict the whole idea of 3D documentation. Meanwhile, apart from the wow effect of having an interactive 3D-representation of the documentation, the adverse consequence of not aligning our documentation end-goal with the capabilities of 3D-recording means that the geometrically highly detailed documentation is often reduced to a 2-dimensional orthophoto, which may be vectorised and treated like a traditional paper drawing. This is for the most part how 3D SfM is applied to field archaeology at the moment – as a tool for creating very precise distortion-free documentation photos. It worked very well in Alken Enge. However, it also meant not dealing with 3D documentation on its own terms. Three objectives were defined, targeting explicitly the inability to exploit the full potential of the 3D representations:

- The development of a flexible solution for integrating archaeological interpretation and 3D geometry was considered the main challenge, and the lack of dedicated software, which allow for embedding classification data into the 3D-models was regarded as a severe limiting factor. By segmenting the geometry, and splitting it into its constituent parts corresponding to individual archaeological entities, an enhanced level of interaction with field-recorded 3D models as well as augmented semantic value could be achieved.
- An integrated database was needed, which could hold not only the 3D data and its associated classification data, but also provide para-data tracking associated with the documentation pipeline, using the data model principles of event-based recording.
- An online infrastructure for textural as well as spatial data was needed to accommodate the cross-disciplinary exchange of data and collaborative interpretation.

The digital documentation produced at Alken Enge followed a predefined pipeline involving a number of teams, each responsible for individual steps in the process. Documentation Events of varying size, which by function is very similar to the more traditional concept of Stratigraphic Units, were excavated by trowel and photographed for SfM processing using ground control markers, which were measured by total station. Within half an hour, an orthophoto was generated, printed to scale on paper, laminated, and used in the trench for delineation and interpretation by the archaeologists. This process was later streamlined and made more efficient using High Performance Computing (Stott et al. in press). The orthophoto sketch was eventually scanned, georeferenced and vectorised using ArcGIS. To efficiently manage the incoming data, the documentation hierarchy of Data Collections and Documentation Events was recreated as a folder structure on a file server, and all related and derived files were organised accordingly.

4.4.1 Ortho-projection through Point-In-Polygon

The 3D content was stored in its native proprietary file formats (mainly Agisoft PhotoScan project files), and finally exported to open ASCII .ply Stanford Triangle Format with associated bitmap texture in .png format.

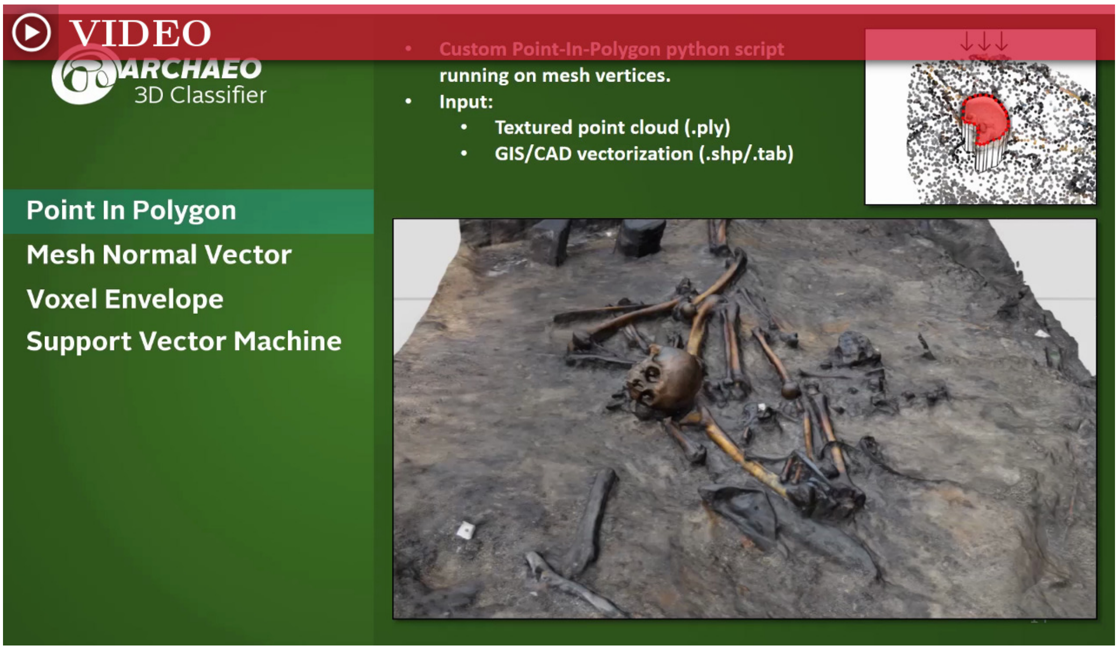

Figure 4.5: Animations illustrating the segmentation concepts: Segmentation by Point-In-Polygon (a), Mesh Normal Vector (b), Voxel Refinement (c) and Support Vector Machines (d). `https://vimeo.com/257346646/dac1e8d17a`

Having GIS vector data representing the archaeological interpretations, as well as 3D models offered an opportunity to use the vector polygons to embed archaeological classification into the 3D models themselves. This process was in part inspired by the work by Wulff & Koch (2012), who demonstrated methods for projecting each triangle in a 3D mesh into a vectorised drawing to determine the archaeological entity to which it belonged, thereby segmenting it into discreet elements. For the Alken Enge project a Python script developed to automatically parse the 3D model. Instead of triangles, it would match each 3D vertex of the mesh against the polygons in the ArcGIS Shapefile. The algorithm used, was a simple Point-in-Polygon routine, which would efficiently segment the mesh into individual .plys for each polygon, named according to the attribute identifier from the GIS-data. Accordingly, all vector-colour data, face-indices and texture coordinates were retained and transferred (see fig. 5.5a).

The segmentation process is not limited to top-down projections, and in the case of Alken Enge, where vertical sections were used extensively to keep track of individual layers and stratigraphy, a combination of local 2-dimensional coordinate systems were used to project vectors onto vertical sections.

An interesting observation was made, during the first tests of Point-in-Polygon segmentation by 2D vectors on the Alken Enge excavation data. There was excessive focus on segmenting the 3D model according to the individual finds, such that the actual surface on which the finds were placed was almost overlooked. However, it also needed segmentation. For practical purposes, any such 'background' or surface mesh would usually be much larger than any segmented find, and it was decided to simply segment any geometry, which was not inside a polygon into 1 square-meter blocks, so that they could be managed and loaded, alongside the segmented objects, at a comparable speed.

4.4.2 Mesh Normal Vector refinement

Due to the nature of projecting an orthogonal vectorisation onto a 3D surface, there are some noticeable limitations to the segmentation process, which were also identified by Wulff & Koch (2012, 95–96). The main issue concerns how protruding objects or convex sides may inadvertently be segmented alongside neighbouring entities as a result of the 2-dimensional projection. One positive thing is, however, that in working on surface geometry as produced by SfM, overlapping geometry within one Documentation Event is relatively rare. Furthermore, it is possible to employ the face-normal-vectors – i.e. the 'way' each triangle in the mesh is facing – to identify sections, which are perpendicular to the orientation of the projection and use them to refine each segmented object. The face-normal-vector may be progressively computed by its three vertex coordinates as part of the segmentation process, or derived from the original ply (see fig. 4.5b).

4.4.3 Voxel Envelope and Support Vector Machines

Whereas both of the above use the archaeological interpretation as a starting point for the semantic segmentation, another option is to turn the process upside down. This means allowing the computer to suggest archaeological entities on the basis of predefined criteria for geometry and texture.

One solution is to convert the surface geometry into a volumetric model. By generalising the model into a voxel matrix, of a fixed value of for example 1 cm, it is possible to make continuous sections through the model, and identify closed loops, which correspond to physical entities protruding from the surface, and refine the proper extend for a 2D vector representation (see fig. 4.5c).

Another option is to employ Support Vector Machines (SVM), and disregard geometry as the defining basis for segmentation altogether, and instead focus on colour and texture. For SVM to work, a training dataset is needed, but due to their heterogeneous appearance, the human bones from Alken Enge were the not the best subject for this procedure. The vertical sections with hundreds of layers, reflecting the sedimentation sequence in the wetlands, are however characterised by some distinct differences, as are the postholes which penetrated the sandy lakebed. A combination QGIS using LibSVM and OpenCV through the Monteverdi and Orfeo Tool Box plugins allows the use of existing vectorisations in combination with orthophotos to segment flat geometry on basis of feature or context colour and texture (see fig. 4.5d).

In both cases, a starting point with machine assisted processes for the segmentation and classification of features is an interesting basis for collaborative evaluation and analysis.

4.5 Fragmented reality in a 2-dimensional representation

The Alken Enge project involved a number of interdisciplinary scientific partners with individual aims of analysis, who would feed into the overall questions regarding the site. For example, how were the deposits created and what is the context of the prehistoric landscape, what had happened to the human bones, and were the people local or foreign? Additional overarching methodological questions regarding the dynamics of water levels in a wetland area in terms of preservation conditions and decomposition of organic artefacts were also in focus. All these aspects have a geographic and spatial component, as is usually the case with archaeology. However, the various disciplines also applied different methodological approaches to scientific questions, and, in turn, an array of different tools and procedures. Consequently, the project faced a challenge in dealing with data fragmentation. This was particularly the case when working with desktop GIS, which produces a multitude of intermediate and supporting files for each dataset and with SfM, which takes hundreds of input photos. To accommodate this variety, Documentation Events were defined for each individual data contribution, including information and metadata describing the method of analysis and software used. During the excavations, an interesting observation was made regarding the workflow, which relates directly to what may best be described as a paradigm of file-based thinking. Archaeologists have become accustomed to using primarily desktop applications for doing digital archaeology, and the conflation of spreadsheets, photos, GIS and CAD tables all contribute to a workflow, which is of limited flexibility. In terms of collaboration, this also means that infrastructure in support of file-sharing becomes a priority, but leads to a discontinuity where data very easily becomes fragmented. When it comes to the 3D content, another level of discontinuity exists, which relates to the human-computer interface being almost exclusively 2-dimensional. We interact with a 3D model, through a 2-dimensional projection onto a computer screen, and conversely, we aim to shape 2-dimensional surfaces by trowel and shovel in the real world, which may be visualised by the available tools. As more online solutions are introduced to the documentation pipeline for data entry and recording, and more immersive means of human-computer interface become available, one cannot help to speculate how this online thinking will affect the workflow; but also what it means for 2D vs. 3D archaeological thinking (Benko, Ishak & Feiner 2003; Eve 2012). Having immediate access to an interactive online 3D representation of an ongoing excavation has far-reaching implications. Not only does it affect the collaborative preconditions of archaeological fieldwork, but it is associated with a paradigm shift in archaeological recording, represented by the adaptation of fully digital methods, workflows, and data (Berggren et al. 2015; Roosevelt et al. 2015). A web-based 3D platform facilitates the exchange of knowledge, for instance between archaeologists and geologists, regardless of terminology and tradition, and instead focuses on the photo-realistic and geometrically accurate visual representation, and the individual researcher's perception and interpretation thereof. It helps archaeologists account for depositional sequences and stratigraphic observations while the excavation is on-going, and provides an immediate three-dimensional spatial context to all finds and features. All observations, interpretations and derivatives go together in one internally consistent management system, which reflects the excavation process and the iteration of hypotheses, and which is accessible globally.

4.5.1 Database and Scraping

For the Alken Enge project, an online database was developed and used for direct data entry in the field. At the time of the excavations, the requirements for managing 2D and 3D content were ambitious enough that it was regarded too complex to achieve by a purely web-based solution. Development therefore began of a cross-platform client application with an online PostGIS enabled PostgreSQL-database, compiled for both Windows and Mac computers (ArchaeYA). It had a Python 3.4 core and used Qt5 support libraries for the user-interface and OpenGL rendering. During development it became clear, however, that a dedicated desktop application, was not necessary to fulfil the requirements of 2D and 3D navigation. These criteria could be met using HTML5 enabled browsers and JavaScript instead. ArchaeYA was replaced by a solution – Archaeo (Jensen 2017a) - which included a flexible custom-built user-interface, resembling the original client application, but written in PHP with a MySQL database back-end. The database is subsequently undergoing continuous development and being repurposed to suit other projects' needs. PHP was chosen based on its open source philosophy, availability and support from almost any webhosting company, while MySQL was also chosen for its support for geometry data-types. Consequently, all field recorded observations regarding finds and contexts were immediately available online, while associated GIS-data would be uploaded to the database as Well-Known-Text (WKT), following open standards and best-practices for archiving (Archaeology Data Service 2015). The hierarchy of Data Collections and Documentation Events was recreated as a folder structure on a file server, while a Python script was developed to act as a scraper. The ArchaeoScraper module will iterate through any folder structure, and build SQL insert statements on the fly, based not only on file contents, but using the folder hierarchy and naming conventions to insert the required relations between database records.

- Different folder structures, naming conventions and file types are treated according to one of several predefined XML schemas.
- GIS vector files are interpreted and transformed from any native coordinate system using pyproj libraries to a common web-friendly WGS84 projection (EPSG: 4326).
- All JPEG photos are furthermore parsed for embedded EXIF-data regarding exposure, focal length etc.
- The 3D content based on ASCII .ply files with associated .png bitmap textures, is also parsed and added to the database as JSON-data, including vertex, face and normal data as well as texture-coordinates.
- Database records are inserted for each segmented 3D model, and appropriate database relations are created to ensure database integration between not only 2D vector data and 3D models, but also the textual classification data.

For practical purposes, a transformation was applied to all coordinates, effectively shortening them. This made for more efficient storage and helped avoid problems when visualising using a GPU, with limited floating point precision, which would result in "blocky" geometry. Finally, the script creates a checksum calculation for any interpreted file, and adds it to the database as a reference to the source file, meaning that it is possible to trace back any scraped data to the original file.

The scraper effectively combats the data fragmentation brought forth by the file-based documentation, and furthermore allows different collaborators to work with the tools they usually do. For instance, almost any GIS, CAD and 3D software may be used to generate documentation data in a file-based folder structure, as long as it is done according to a well-defined schema of folder structure and file types for harvest by the scraper (see fig. 4.6).

4.5.2 An online 3D viewer for segmented data

The most obvious advantage of a web-based database and 2D/3D viewer is perhaps that, unlike desktop applications, which require software installation of required dependencies on the user's computer, JavaScript APIs are loaded alongside the web page, and the necessary code is executed on the client browser, without the need for any pre-installed browser add-ons.

The Archaeo 3D viewer takes advantage of the open source three.js JavaScript APIs, which provides a wrapper for all the common OpenGL functions. Using the database Documentation Events, 3D data is loaded directly from the MySQL database to the client browser as JSON text, where it is parsed and combined

Figure 4.6: Example of folder structure and scraper schema.

to build renderable, segmented 3D models. Using WebGL for visualisation of 3D models does however have some implications, as pointed out by the MayaArch3D project (Auer et al. 2014). It relies exclusively on the client browsers JavaScript engine to interpret and execute the code, and client computer hardware and – not least – network speeds quickly become a limiting factor, when transmitting the millions of vertices, face indices and texture-coordinates, which make up a 3D model. Contrary to desktop applications, browser JavaScript has limited memory management, meaning that it is very easy to completely deplete all available memory when loading large or complex 3D scenes.

The 3DHOP-Viewer addresses these limitations by utilising the Nexus file format for transferring 3D data (Ponchio & Dellepiane 2015). It allows for progressive multi-resolution loading, which means that the 3D model is rendered in increasing detail before the entire file has been downloaded to the client. In the case of the Archaeo 3D viewer, the 3D models are queried and transmitted as segmented elements, giving the appearance of progressive loading as each part is renders as soon as it is transferred. Furthermore, the use of asynchronous loading through JavaScript effectively allows for more segments to be downloaded simultaneously. A segmented mesh of around 250.000 vertices, including texture bitmap is usually completely downloaded in less than 10 seconds, which is an acceptable speed for most uses.

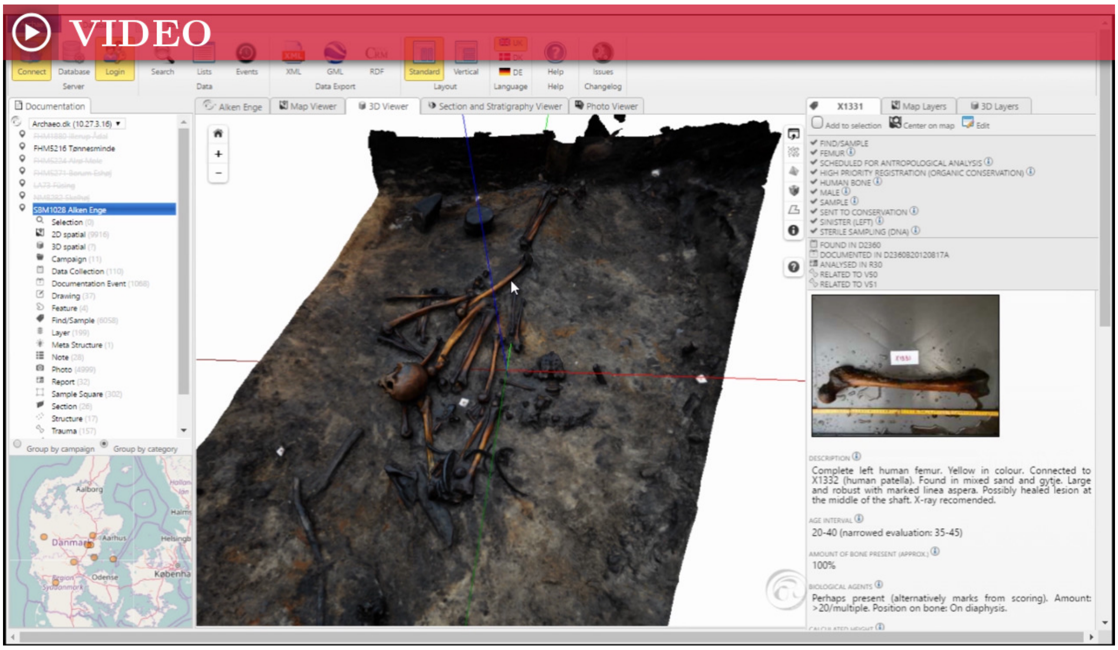

Figure 4.7: (VIDEO) Screencast of the Archaeo online database, demonstrating basic navigation and the integrated segmented 3D mesh of the Archaeo 3D Viewer.
`https://vimeo.com/257346674/6f4d06a3a2`

Unlike the ADS 3D and MayaArch3D viewers, the Archaeo 3D-viewer does not explicitly distinguish between archaeological objects/finds and stratigraphy, but allows for the segmented data to be accessed as either. Due to its special attention to the photo-realistic excavation documentation, it is targeted at the visualisation of Documentation Events. This also means that the user has an option to choose to either display 3D objects as individually segmented objects or as part of a larger documentation unit. Different 3D representations of the same element are therefore accessible independent of the entire 3D Documentation Event to which it belongs. It does however have the adverse effect that individual segments load at very different speeds, according to their complexity, i.e. number of 3D primitives (vertices, faces etc.).

Compared to the ADS 3D Viewer, which makes use of clickable hotspots to provide the linking to associated data, the Archaeo 3D-Viewer provides a different level of semantic classification, as each individual segment is directly selectable from the mesh. This has the clear advantage that it resembles the way people are used to interact with 2D vectors in GIS and CAD – much like selectable polygons, but may not be as intuitive as visible hotspots are – depending on the target audience. It does, however, provide an integrated link between 2D GIS-data and 3D model-data as well as semantic classification, all in the same data model, and it is possible to overlay the associated segmentation vector onto the 3D-model, visualising the para-data surrounding the segmentation process (see fig. 4.7).

4.5.3 Combining 2D, 2.5D and 3D

The combination of 2D and 3D in a web GIS solution for archaeology is rare, but has been realised by MayaArch3D for instance (Agugiaro 2011; Auer et al. 2014). One of the more elaborate projects uses semantically structured 3D models for archaeological site management at Pompeii (Apollonio, Gaiani & Benedetti 2012), while Auer (2012) has demonstrated the analytical capabilities of WebGL-based web GIS.

The Archaeo database employs the open source leaflet.js JavaScript libraries for visualizing 2D components; mainly GIS-derived vector data. This provides for a lightweight, flexible and customizable mapping interface, which integrates not only web-service background map data (WMS and WFS), but allows for spatial queries into the 2D geometries in the MySQL database.

Given that both archaeologists and geologists made extensive use of soil sections at Alken Enge incidentally helped highlight another challenge, which is easily overlooked and leads back to the legacy of archaeological 2-dimensional methodology, namely the management of vertical sections.

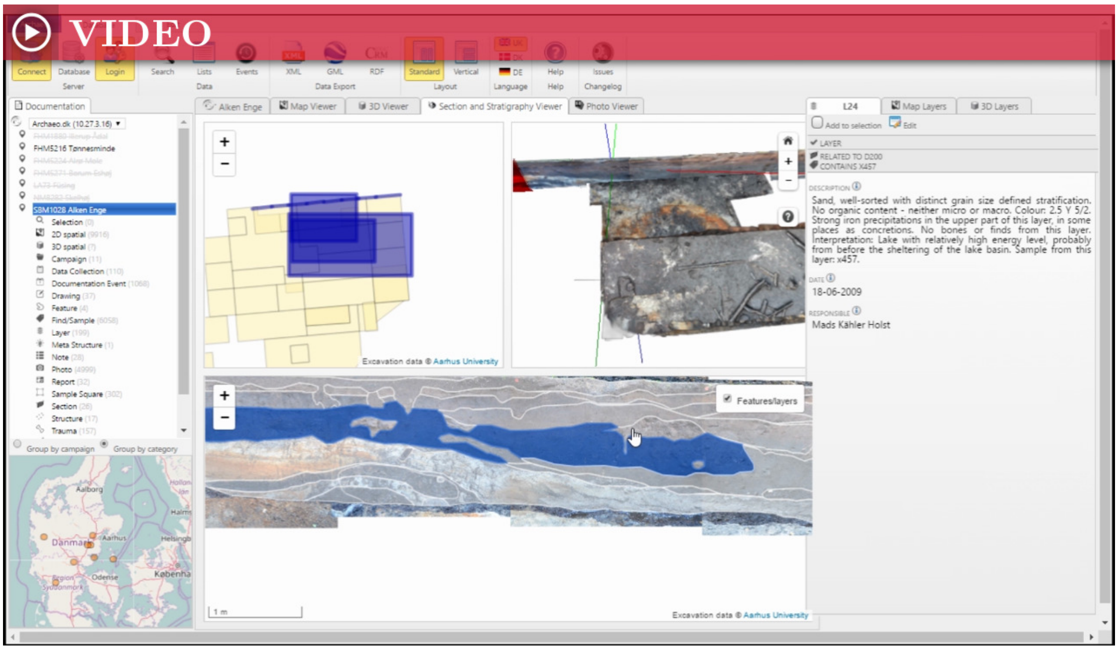

Figure 4.8: (VIDEO) Screencast of the Archaeo 3D viewer, demonstrating navigation through pseudo-3D vertical sections and horizontal planes, derived from 2D-georeferincing information. `https://vimeo.com/257346712/a386fd28f0`

Vertical sections are commonly featured as separate datasets, detached from the rest of the spatial documentation – this applies to both traditional analogue drawings and GIS. The 2-dimensional projection, which is perpendicular to the usual top-down projection is incompatible with any GIS projection, and is therefore predominantly managed as separate datasets in local, vertical coordinate systems. The necessary information is, however, usually available to perform a scientific augmentation of the 2-dimensional profile sections, and arrange the sections in their proper place and orientation in 3D space, albeit as flat 2D-surfaces. The same applies to both 2D rasters, such as orthophotos, and 2D vectors. In the case of georeferenced othophotos, a GIS world-file will usually contain information about proportions, while the associated GPS or TPS –measurements provide the necessary data for placement and orientation. The properties (origin/orientation/scale), which are automatically harvested and derived by the ArchaeoScraper, and used to automatically "raise" and unwrap the 2-dimensional profiles at their proper location in 3D-space (see fig. 4.8).

4.6 Conclusion - the collaborative potential of online 3D frameworks

As a case study, the Alken Enge excavations are atypical in terms of the type and complexity of archaeological and geological deposits. In fact, excavation complexity is often the primary rationale for employing an SfM workflow; for instance at recent excavations at Star Carr (Milner et al. 2013) and Çatalhöyük (Berggren et al. 2015). For the more ordinary excavation situations, i.e. large-scale surface recording of soil features and postholes, the stratigraphic component is less complicated and the use of 3-dimensional documentation provide limited extra information. The consistent use of photogrammetry should, however, not be understated as its visual constituents offer unique collaborative capabilities – 3-dimensional or not.

In the case of Alken Enge, the interdisciplinary collaboration between archaeology and geology was very rewarding in terms of understanding and discussing how different events in the past lead to the creation of individual stratigraphic sequences, but also in recognising how individual scientific disciplines approach the same material evidence differently. In particular, the divergences between an archaeologist's and a geologist's interpretation of a soil section, and how differing professional traditions shape the documentation outcome, became very apparent. Archaeologists focus on evidence of human activity, while geologists are looking for physical processes. In either case, documentation and interpretation is a matter of identifying the abstract notion of something, which is not necessarily a physical entity like an object or artefact, but a context of some previous human action or natural event (Jensen 2017b; Madsen 2003). For the purpose of recording these observations in their entirety, we may make use of online frameworks as more than dissemination outlets, and accommodate documentation of the entire process of knowledge creation.

In practice, the use of Documentation Events demonstrates the kind of real-time collaboration which online 3D visualization makes possible. In particular, it offers the virtual presence of researchers, who are physically distant, but who are able to give their informed opinion, based on an interactive 3D-visualisation, while an excavation is ongoing. Thus, different versions of the same 3D-documentation are submitted and correlated, but segmented and annotated individually according to different interpretations. There is no one "real" interpretation, but a series of Documentation Events, which provide input to a common Data Collection.

The combination of online frameworks and photogrammetric 3D documentation also has implications for the more general excavation methodology. While the majority of excavations adhere to some level of single context archaeology, the use of Documentation Events acknowledges the subjectivity of archaeological interpretation, and the fact that hypotheses should not be set in stone, but be open to re-interpretation and used to guide the excavation progress. A consequence of traditional single context recording is that individual archaeological features easily become "locked" into the concept of a stratigraphic unit, which is fixed in time and space, and documented only once, before it is removed to reveal the next context in the sequence. Furthermore, 3D photogrammetric recording tends to include more than the archaeological context itself, such as any artefacts and surrounding or protruding features, simply because they are 'part of the scene'. Thus, the Documentation Event allows for the same object to be documented several times, which may be used to account for any physical decay or movement of objects engineered by the excavation process itself. The clear advantage of having an infrastructure for visualising 3D documentation is the ability to visualise not only any matrix of stratigraphic units or documentation events in their proper vertical sequence, but it also acts as a tool for documenting the excavation process itself, and how it impacts on the archaeological features. Being such an affordable and time-efficient way of doing field recording, SfM provides far better conditions for documenting the process, in particular, the observations made in the intermediate stages between stratigraphic units and while excavating one context in preparation for the next. This way, observations which would usually not be recorded or considered too time-consuming to draw by hand, become part of the bulk photogrammetric evidence.

The online infrastructure facilitates data-entry in the field, and having both 2D GIS and 3D photogrammetric interactive visualisation capabilities on the same platform delivers immediate accessibility in support of cross-disciplinary and collaborative research and knowledge exchange. An added benefit is the data accessibility, which allows for data reuse. In the case of the Archaeo framework, the augmented semantic value of having integrated textural and spatial components provides the means for far deeper queries based on archaeological classifications, compared to ordinary GIS attribute tables, and users are encouraged to use the online search functions for the purpose of exporting data to be reused and analysed in other contexts under an Open Data Commons Attribution License. A hitherto unexplored potential of the Archaeo framework is the combination of the segmentation of 3D models with the semantic web and its possible use of crowd sourcing. The 3DSA: Semantic Annotations for 3D Artefacts, for instance, does exactly that, and use crowd-sourced semantic annotations to streamline the cataloguing of 3D museum artefacts (Hunter & Gerber 2010; Yu, Groza & Hunter 2011). Having an online framework, which is focused on visualisation and interaction, it is possible to take advantage of the contributions of citizen science. Not only will this aid in the scientific augmentation of legacy data, but assist professional archaeologists in working through an increasing amount of recorded visual data.

As the scientific and digital revolutions change the basis for archaeological knowledge creation, the act of observation – and potentially re-interpretation – is moved from the physical trench to the online visualisation.

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5

Beyond 3D: Extending Dimensions of Image-based Documentation in Archaeology

Jensen, P.; Stott, D. (manuscript ready for submission)

Abstract: In this article, we examine the potential of using supervised classification approaches on image-based excavation 3D data to assign archaeologically relevant interpretations and delineate volumes. This serves to accentuate the challenges we face in integrating 3D as archaeological documentation. To fully employ 3D documentation within archaeology and take advantage of its semantic, analytical and data management capabilities, we must be prepared to reassess the way we acquire and analyse our primary data. We should also be prepared to consider alternate types of data representations, which do not necessarily fit into our usual conceptual framework of observation and interpretation.

We propose moving beyond 3D reconstruction by easing the burden on the archaeologist as the sole source of interpretation, and introduce an epistemological tool which complements the interaction between the empirical world and our abstraction of reality. The new inferential tool extends and supplements our methods and changes the dialectics concerning archaeological field recording data. It provides a new sensory interaction with the documentation. We aim to point out the epistemological and analytical potential of alternative goals of archaeological recording compared to what traditional or image-based 3D-recording currently offer.

5.1 Introduction

Image-based 3D reconstruction has been transformative in archaeological recording. It enables detailed measurement of morphology at levels of detail hitherto unimaginable. However, the information produced by these workflows is not utilised to its full potential (De Reu et al. 2014, Forte 2014, Forte et al. 2015, Galeazzi 2016). The data produced are either used as analogs for traditional recording techniques such as plan and profile orthophotos, or 3D models that tend to be viewed as an end-product in and of themselves. When archaeologists eventually choose to go 'full 3D', it frequently affects the archaeological knowledge creation by causing a preoccupation with the pursuit of the most geometrically accurate recording of reality. The 3D representations, no matter how accurate, may be visually inspected, but not easily analysed or integrated into the documentation in three dimensions. There are, however further dimensions to these data that have been neglected in archaeological recording.

In particular, the spectral properties of the recorded models are often ignored. RGB digital cameras are multi-spectral sensors. Each of the three bands recorded by the sensor provides a measurement of reflectance of objects in the frame at different wavelengths. This enables inference of material properties from the reflectance data. Absorption features relating to soil moisture, humic and ferrous oxide content are all detectable in the visible spectrum (McCoy 2005). Remote sensing approaches to soil classification have long used these properties in airborne and satellite data to distinguish differing soil types (Mulder et. al 2011, Stoner & Baumgardner 1981). Both supervised and unsupervised classification methods are widely applied, and make extensive use of machine learning algorithms to discriminate material properties from reflectance data (Mountrakis et al. 2011).

This enables knowledge to be derived from large volumes of image data, and presents a possible solution to some of the challenges implicit in image-based 3D recording. Classifying and segmenting these data manually is a daunting task. Interacting with the data is not straightforward. Currently, everything is mediated via a two-dimensional projection onto a flat screen, although developments in virtual reality promise to change this. GIS and CAD software have limited capabilities handling complex 3D surfaces and volumes with their associated aspatial data. Additionally, the sheer volume of data generated in a typical excavation entails significant work to add meaning to the data. In particular the fragmented use of measurements and points from GPS and total station in combination with derived vectorisation, and an increasing amount of images and other remote sensing data, which require further processing before becoming useful as documentation.

Machine-assisted processes for the segmentation and classification of information-rich 3D content provide the opportunity to address many of these issues. The human input would then be better invested in evaluating, interpreting and classifying the outcome. For instance, the use of delineation is probably the most common element in the conventional archaeological recording toolkit, but how does a line in 3D-space make any sense? A two-dimensional object such as a line has no volume and therefore cannot logically exist in a three-dimensional representation. A 2D polyline only exists in 3D space at the intersection with an imaginary or physical plane. 3D polylines conceptually make most sense, when acting as edges in wire-frame models, used to describe the faces of a 3D mesh, which is fundamentally different from interpretative two-dimensional delineation. Archaeologists are interested in analysing volumes: which artefacts are contained within a specific volume or fill? What is the interrelationship between volumes? We are so interested in the two-dimensional line or polygon abstraction we use to generate a plan or map.

In this paper we examine the potential for using supervised classification approaches on image-based excavation 3D data to assign archaeologically relevant interpretations and delineate volumes. This serves to accentuate the challenges we face in integrating 3D as archaeological documentation. To fully employ 3D documentation within archaeology and take advantage of its semantic, analytical and data management capabilities, we must be prepared to reassess the way we acquire and analyse our primary data. We should also be prepared to consider alternate types of data representations, which do not necessarily fit into our usual conceptual framework of observation and interpretation.

5.2 Case study: An unremarkable posthole

The test case chosen for this study is not one of extreme complexity compared to the deep stratigraphic layers of urban archaeology (Roskams 2001, Carver 2009, Collis 2011). Instead, it represents the bulk of current rural excavation activity in Northern Europe, where open area excavation of features representing postholes and pits are excavated as part of the everyday routine of contract and rescue archaeology (Kristiansen 2009, Everill 2012). Although excavation practices differ, the aim is similar; focusing on fast, consistent excavation and recording of soil features. When not dealing with complex stratigraphic sequences, the information revealed by the individual posthole is limited, and can be viewed as a quick-and-dirty test of hypotheses: is this actually a posthole or another phenomenon, and does it resemble features nearby, and thereby a part of a larger structure i.e. a building? Various archaeological traditions approach the characterisation and excavation of these features differently (Felding & Stott 2013). Either interfaces are identified and interpreted and stratigraphic units are removed individually, or arbitrary sections are made through the feature, in plan or in profile, without the limits of investigation respecting the limits of the stratigraphic units. In either case, the archaeologist is trained to look for and identify interfaces between layers. Essentially, it is these borders between fills of different colour and texture which define interpretation, rather than the actual fills. The obvious downside to the box

Figure 5.1: The Iron Age Longhouse (on the left) at the site FHM5216 Tønnesminde, Samsø, Denmark. Only postholes from the roof-bearing posts were preserved. Feature A712 (on the right) is one of the roof-bearing posts and used for this case study. The feature appeared as two intersecting individual features side by side. This photo depicts the situation immediately prior to the 21 box-sections, which were expected to reveal stratigraphic relations between the two parts.

cut is that half of the posthole is removed to produce the section, and everything beyond the section remains undocumented.

In this case study, we deal with a well-known structure; two parallel rows of 10 evenly spaced postholes, attributed to an Iron Age longhouse (see fig. 5.1). Eight of them were excavated using traditional methods of sectioning and drawing, while two were chosen for the case study. All postholes were additionally documented using a Structure from Motion workflow (De Reu et al. 2013; De Reu et al. 2014).

To acquire useful data for a volumetric model, a stereological approach was adopted. Stereology quantitatively examines properties of objects by slicing them at discrete intervals to produce three dimensional information (Mouton 2002). Applied to archaeology this means instead of following and documenting subjective surfaces defined by the archaeologist, arbitrary, systematic, sections were made through the feature and recorded individually using Structure from Motion. This is massively redundant for the the majority of archaeological features, and is not proposed as a practical excavation methodology, but is used here as a proof of concept.

The posthole considered in this study is completely unremarkable, consisting of a cut, infilled with re-deposited subsoil packed around a post. Diffuse interfaces between layers resulting from bioturbation and leaching mean that that both the position of the post and the exact boundary of the the posthole were hard to identify, especially at the base of the cut, where the darker, gleyed subsoil was very similar in colour and texture to the fills. This makes it both representative of thousands of its kind, and a challenging test for the methods evaluated below.

5.3 Method

An arbitrary bounding box surrounding the posthole was set out using a total station and control point markers were positioned to provide common georeferencing for all subsequent documentation events. The sectioning of the posthole started just outside its maximum extent at the surface, followed by 21 sequential vertical sections, each time shifting the section a few centimetres, parallel to the previous one. Each section was documented by c. 10 photos from various angles for Structure from Motion, resulting in point clouds of an average of 150.000 coloured 3D points per section, totalling around 3 million points for the entire feature.

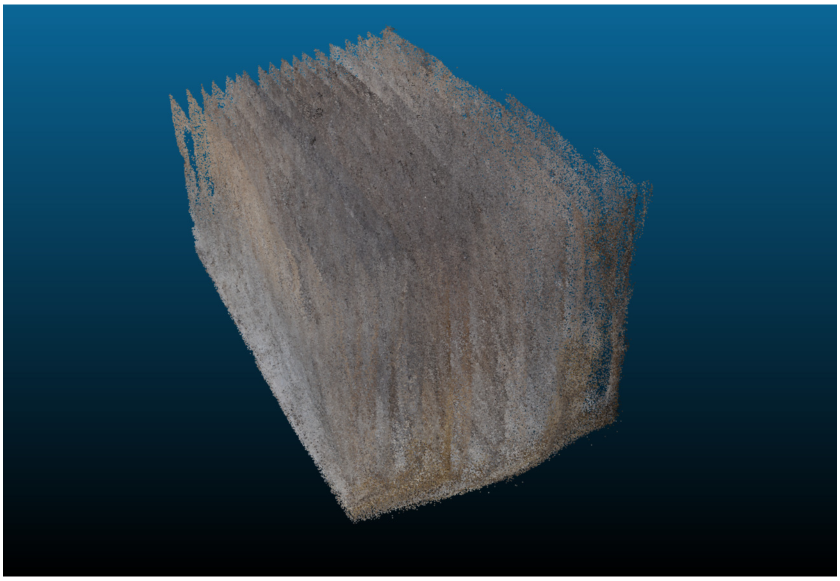

Figure 5.2: Point cloud before classification. The individual sections provided by individual SfM processing are clearly visible.

RGB values for the fill and subsoil layers (see table 5.1) were extracted and used to train an SVM (Support Vector Machine) classifier. SVMs are discriminative classifiers that attempt to identify an optimal plane dividing classes with the greatest margin of separability (Cortes & Vapnic 1995, Smola & Schölkopf 2004). Data to be classified are then separated and assigned to classes using these planes. This performs well for large multi-dimensional datasets such as those considered here. For this reason SVMs are commonly used for land cover classification of remotely sensed imagery (Mountrakis et al. 2011, Meglani et al. 2004), character recognition (Chen et al. 2001), and identification of proteins and chemical compounds in biochemical analyses (Brown et al. 2000). The analyses in this study were performed using the Scikit-Learn Python package (Pedregosa et al. 2011).

Finally, the point cloud was projected to a volumetric 3D matrix using a nearest neighbour algorithm with averaging resampling for the RGB values. The resultant

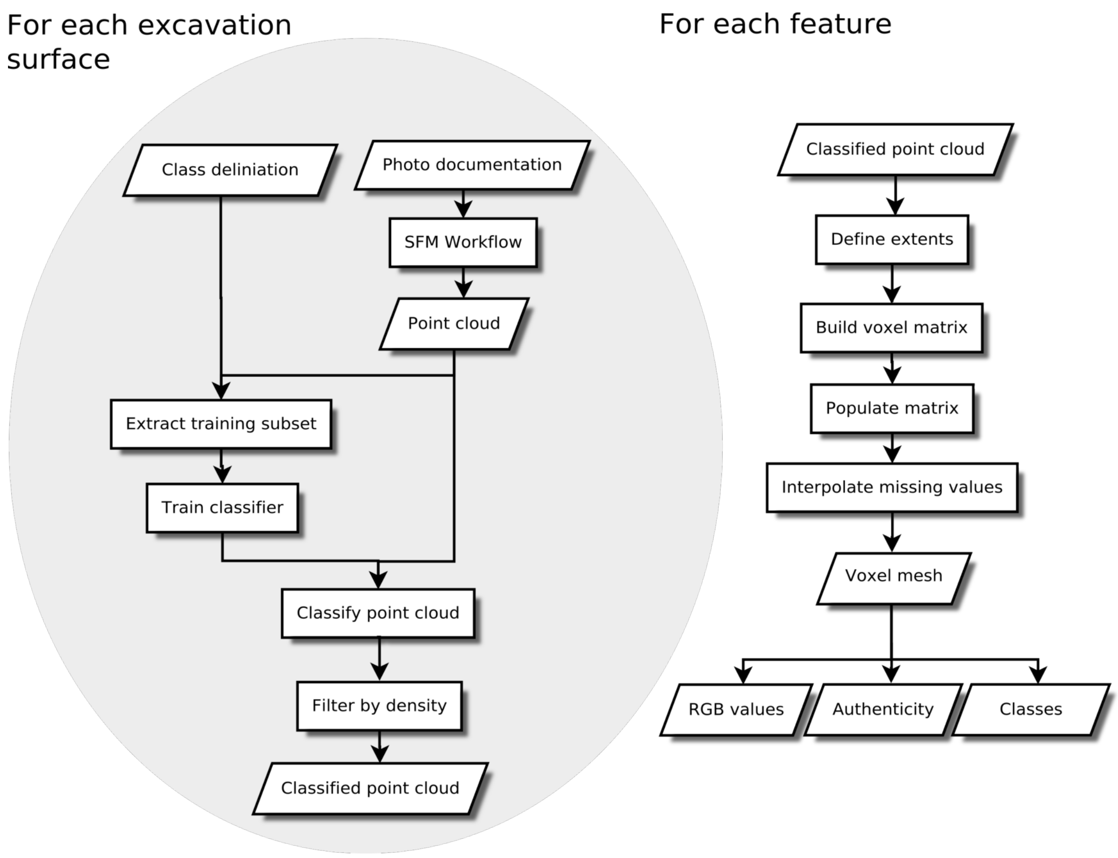

Figure 5.3: Workflow

Table 5.1: Confusion matrix: SVM predictions

n = 137835	Fill	Fill density (filtered)	Subsoil	Subsoil density (filtered)
Actual fill	34392	34028	4048	4422
Actual subsoil	25610	3803	73775	95582

voxel model allows for other types of visualisation as well as spatial and quantitative analyses on volumes, and ad-hoc sections through the model (see fig. 5.4).

5.4 Classification

The resultant classified point cloud showed a large number of false positives. This is expected, as the soil is a mixed and heterogeneous material, and the gleyed soil at the base of the cut was similar in colour to the fills of the posthole. However, the the spatial frequency of points representing false positives was much lower than those of the correctly classified points. It was thus possible to refine the classification using the point density for each classification.

The SVM classifier was able to distinguish between the fill of the posthole and the surrounding subsoil (see table 5.1). 78% of points were classified accurately, with a false positive rate of 26%. This is far from ideal, as it makes identifying the boundaries of the feature difficult. However, the false positives were spatially dispersed, likely representing fill and humic material incorporated in the subsoil by bioturbation. The accuracy of the classifier was greatly improved by segmenting the points using the density of points of the same classification within a 5 cm distance. This resulted in 94% of points being classified correctly, with a false positive rate of 0.04%, albeit with a slight increase in false negatives.

However, the resultant dataset could not with any certainty delineate the bounds of the fill. Instead, the result indicated a 'gradient of confidence', where the classification became more ambiguous moving from the centre of the feature to the edges. This is to some extent an accurate reflection of the diffuse interfaces between the feature and the subsoil, and the drying of the soil near the surface. The uncertainty of interfaces is often articulated in archaeological recording, but it is very rarely quantified spatially. Such levels of uncertainty are notoriously time consuming and challenging to document using conventional methods. A feature is identified, defined, and this definition is recorded. It is then subsequently tested as a hypothesis by excavation. This requires definitions recorded to be both categorical and canonical, but reality is often less clear-cut. Interfaces are poorly defined, and it can be difficult to define where one stratigraphic unit ends and its neighbour begins.

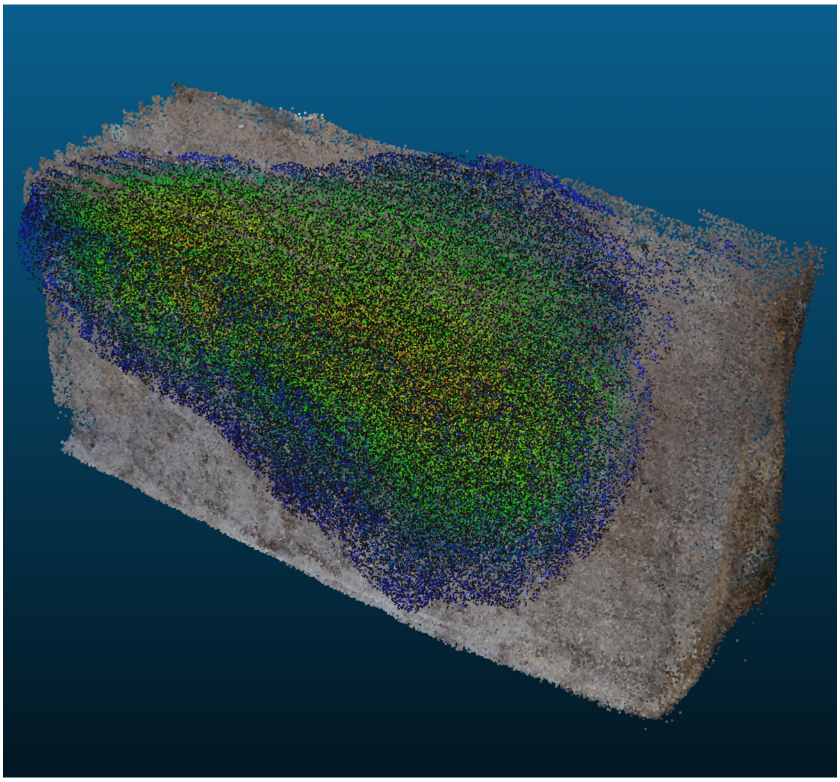

Figure 5.4: Point cloud after classification. The green and blue areas are the identified posthole 'fill' and posthole 'cut' classes respectively .

5.5 Volumetric Representation

For visual inspection, 3D point clouds are a powerful asset, which are relatively lightweight compared to detailed textured 3D meshes. If dense enough, a point cloud will take the appearance of a solid surface, and even outperform 3D meshes in terms of representing reality. Meshes on the other hand are derived from an interpolation of this initial dataset. Point clouds are also common to various methods of 3D acquisition i.e. laser-scanning and Structure from Motion. Besides the geometric point-distribution, the analytical potential of a raw point cloud is defined by the associated attributes, such as RGB values, but closer inspection will reveal that it is still a representation of a series of surfaces, and not a solid volume, suitable for volumetric analysis.

The use of voxels has so far been most extensive in research fields like seismic prospection for underground resources (Koketsu et al. 2004) and medicine as a framework for visualising CAT and MRI scans (Caon 2004, Giovannetti et al. 2016). Although the direct link between the inner-workings of the human body and an archaeological excavation may appear counterintuitive, there are some interesting commonalities. The MRI produces a non-invasive visualisation of inter-

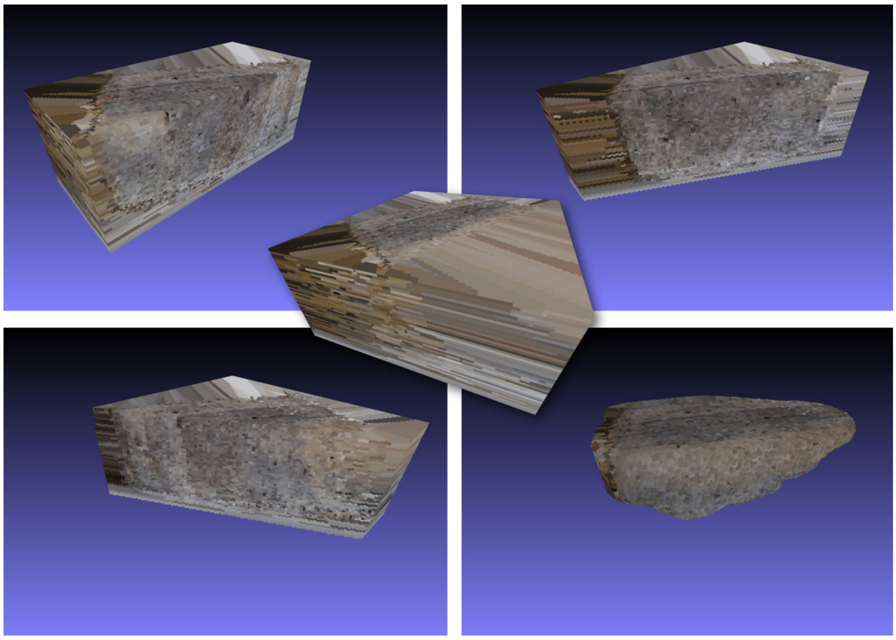

Figure 5.5: Visualised arbitrary cuts throgh voxel matrix, and the posthole fill as a volmetric positive (bottom right).

nal features, which when applied to archaeology is quite appealing. Especially in northern Europe, where most archaeology is soil-archaeology and the most abundant structures are the thousands of pits and post-holes left behind by human activity for millennia. Here, geophysical equipment such as ground-penetrating radar (GPR), multiplexed resistivity and electromagnetic induction are used to identify anomalies, often visualised by grayscale maps (Leckebusch 2003). The anomalous features are however not limited to two-dimensional maps, but retain three-dimensional extends, which is why voxel-modelling has been used more extensively in areas of geophysics (Gaffney et al. 2007, Leckebusch 2003, Schmidt 2014). For archaeological excavations experiments with voxel-based excavation, recording have revolved around adapting the technology to current excavation practices, specifically the documentation of stratigraphically excavated contexts (Bezzi et al. 2006, Lieberwirth 2008a, 2008b, Merlo 2016, Orengo 2013), albeit hindered by the limitations in acquiring voxel data from field recording. What these experiments offer, in contrast to conventional two-dimensional single contexts stacked on top of each other, is a reconceptualization of what is important: it is a way of working with the actual volumes between identified interfaces. This way, instead of dealing with the borders, cuts and surfaces, the fill between them becomes the visual representation.

The abstraction of reality, delivered by the voxel model, is fundamentally different from common visual representations. It is very far from a traditional delineation and yet does not share the same documentation ideal of photorealistic, textured meshes common to image-based 3D documentation. When working with voxels, the chosen level of generalisation is immediately apparent by the size of each little cube, and a high-level generalisation will yield very coarse and 'blocky' representations. Yet the level of generalisation does not determine the documentation quality, as it is a derivative of the more detailed point cloud, produced by laser scanning or photogrammetry, and can easily be redone to fit specific analytical or visualisation purposes.

It is a fairly simple process of projecting and applying a 3D matrix to 3D point clouds, effectively averaging every point - and associated (colour)-information - into neighbouring cubes (see fig. 5.5).

This has the advantage of minimising the separation between sensory data like geophysical surveys and archaeological observation. What is, however, apparent from this procedure is how the documented contexts, i.e. the top and bottom surfaces of a volume, are the only things documented. Everything inside the volume has the same value or description, delivering an inherently flawed model compared to the MRI scan. This boils down to the excavation methods, and the key is a reconceptualization of how we acquire the necessary spatial data in special excavation situations. This is what our sectioned posthole offers.

5.6 Discussion

Data rich recording methodologies are becoming more prevalent in archaeological practice. The increasing ease of application of these methods means it is feasible to record more intensively than we have in the past, as the cost in time and materials for each documentation event is reduced. However, doing so increases the quantity and complexity of the data we generate, and makes it difficult to engage with. Documentation is in essence fractal, where increasing scales of resolution produce more data. Transforming this data into information becomes less achievable for a human interpreter as these trends increase. The data we are able to use are either highly derived or generalised. If we can't use the full data then why do we produce it? By providing a means to classify and segment these data, machine learning approaches have wide-ranging implications and applications for archaeological practice. It extends human interpretation to very large datasets, and makes more intensive, meaningful recording possible.

When combined, the component images of image-based 3D recording like Structure from Motion yield information about spatial geometry. However, the individual images hold information, which is often overlooked. There is spectral information to be extracted from the red, green and blue channels of the image sensor, and paradoxically in pursuit of objective data, we forget how much of archaeology is actually based on the subjective archaeological process of identifying subtle changes and variations in colour and texture. RGB sensor data allows us to formalise this procedure with the aid of the pattern recognition capabilities provided by machine learning.

This is demonstrated in the example presented here. The quantity of data produced by intensively recording a relatively simple posthole (333 photographs, 3 million 3D points each with a red, green and blue values) is significant. By taking our interpretation and using it to train the classifier we can extend a few simple observations to a high-dimensionality dataset containing millions of measurements, using dimensions of the data that are otherwise neglected.

5.6.1 Working with volumes

Making volumes intrinsic to the structure of archaeological data has the potential to enhance our ability to articulate and understand the many human and environmental processes at work in the archaeological record. When using volumes answering questions such as estimating how much turf was used to build phases of a burial mound (Holst & Rasmussen 2013), and thus how many man-hours were entailed in its construction are straightforward, as it becomes a matter of counting cells rather than measuring and calculating differences between surfaces.

Voxel data structures could also allow a finer-grained articulation of temporality within stratigraphic units. A unit resulting from aeolian or colluvial deposition may have taken hundreds of years to form, whereas the posthole discussed in this article was likely created in minutes. Being able to express this information by interpolating time spans to voxels in the model using the stratigraphic matrix in conjunction with dates from within the stratigraphic units. This is not only valuable in analytical terms, but when visualised and animated has the potential to be a powerful interpretive tool.

5.6.2 Interpolation of information

When applied to our posthole point cloud, the sampling frequency, i.e. the individual sections stand out (see fig. 5.6). Especially when slicing the volumetric block perpendicular to the direction of acquisition, the abundance of 'missing information' between the sections is evident. Absence of information is no stranger to archaeology and issues of representativeness, sampling and bias permeate the discipline. However, what if we could use this missing information to say something about the authenticity, certainty and hypotheses related to the recorded data and the representation thereof?

We have chosen to interpolate the point cloud in respect to the predefined voxel matrix, effectively iterating through the three dimensions, allowing each voxel to inherit the colour value of the nearest neighbouring 3D point to fill out any absent information between the sections. Doing so, however, affects the derivative nature

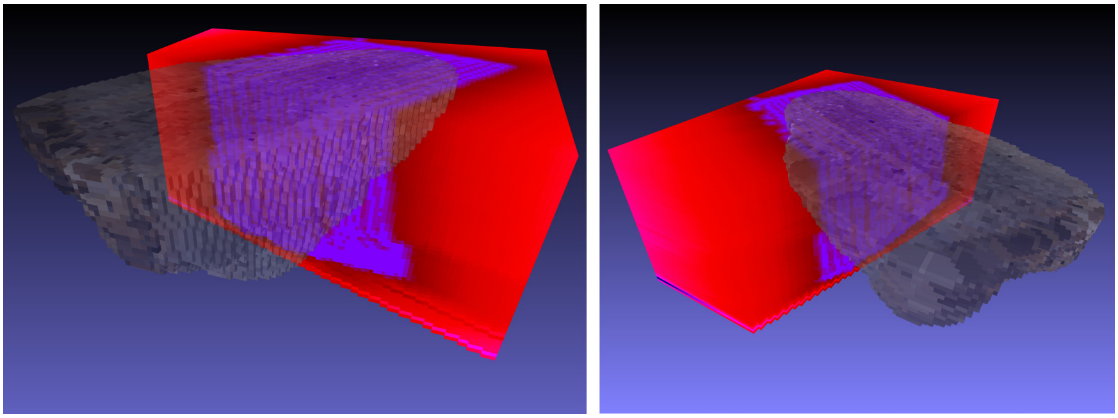

Figure 5.6: Visualising confidence through an 'authenticity-gradient'. Voxels which are spatially nearest to the original point cloud sections are blue, while red voxels are proportionally further away from the observed values.

of the voxels. In our example so far, the voxel and its value refer directly to the value of the point cloud point within or nearest to it. By extending the chain of data, an effort should be made to prevent that the path back to the raw data becomes too long, unless this is well documented. The process demonstrated here projects the point cloud to a 3D volumetric matrix while introducing interpolated para-data information, implemented as a linear function based on varying levels of certainty; a nearest neighbour algorithm with averaging resampling. In working with colour information, there is one inherent attribute which may be used to convey this para-data. In addition to the traditional red, green and blue channels of 8-bit images, the alpha channel is usually used to encode information about transparency in an image. This 8-bit value translates to a number between 0 and 255, but can easily be repurposed, in our case to quantify the level of authenticity in our representation, relative to the observed or recorded properties. For instance, voxels would directly inherit the colour of any 3D points within it, with a 255 alpha-value, resulting in a completely opaque colour, while voxels with interpolated values derived from a neighbouring 3D point would have a value linear to their distance and appear more transparent relative to their distance from 'observed' points. This transparency of the voxel thus tells something about the generation of the documentation and its derivative nature and level of abstraction. The alpha channel can also be used to hold 256 values of discrete data, for instance the individual classes from the SVM classifier, which allows for the segmentation or subdivision into groups of voxels, for instance a complete extraction of a volumetric positive of the classified posthole (see fig. 5.5 bottom right).

Together with the 2-dimensional coverage geospatial model known from ordinary GIS, the voxel model is unique in the way it forces users to evaluate the undocumented or extrapolated data. This is in contrast to the more common emphasis on the observed data, when it comes to documentation.

5.6.3 Extensibility and other applications

Realistically, the applicability of the methods presented in this case study is challenged by the prevalent excavation methodology and the acquisition of data, and as such not a goal in itself. The benefits from doing multi-sectioning of postholes and other features do not necessarily correlate with the time spent. On the other hand, it does not exclude applying the approach to conventional methods. In particular under conditions where the level of human uncertainty in feature recognition is high If the voxel model, for instance, is made from two opposing single context surfaces, the method would still apply. It just means that everything between the two contexts is interpolated and of low authenticity. Even a mixed approach is feasible, as long as it is aligned with the research questions and scaled appropriately.

There are however situations where it would be natural to consider alternative ways of excavating and documenting. The method would, for instance, scale well as an alternative to larger earthworks and barrows, where few sections at intervals are the sole source of documentation data. Having methods that allow for efficient classification and interpolation of the identified volumes, turf and soil types, would potentially increase the scientific outcome.

The SVM-classifiers may also easily be applied to more conventional combinations of ortophoto - posthole datasets in GIS, to aid in the training and identification of features and anomalies (see fig. 5.7).

Other special situations include for instance sites exposed to heavy coastal erosion, where documentation at different time intervals would allow for the documentation of not only the erosion and degradation over time, but would also act as a method for modelling the horizontal and vertical extent of subsurface features, visible in the exposed surface.

In this paper we propose moving beyond 3D reconstruction by easing the burden on the archaeologist as the sole source of interpretations of ever expanding quantities of data, and introduce an epistemological tool which complements the interaction between the empirical world and our abstraction of reality. The new inferential tool extends and supplements our methods and changes the dialectics concerning archaeological field recording data, and whether we apply top-down or bottom-up approaches, if even such a duality exists (Lucas 2015). It provides a new sensory interaction with the documentation. We aim to point out the epistemological and analytical potential of alternative ideals for archaeological recording.

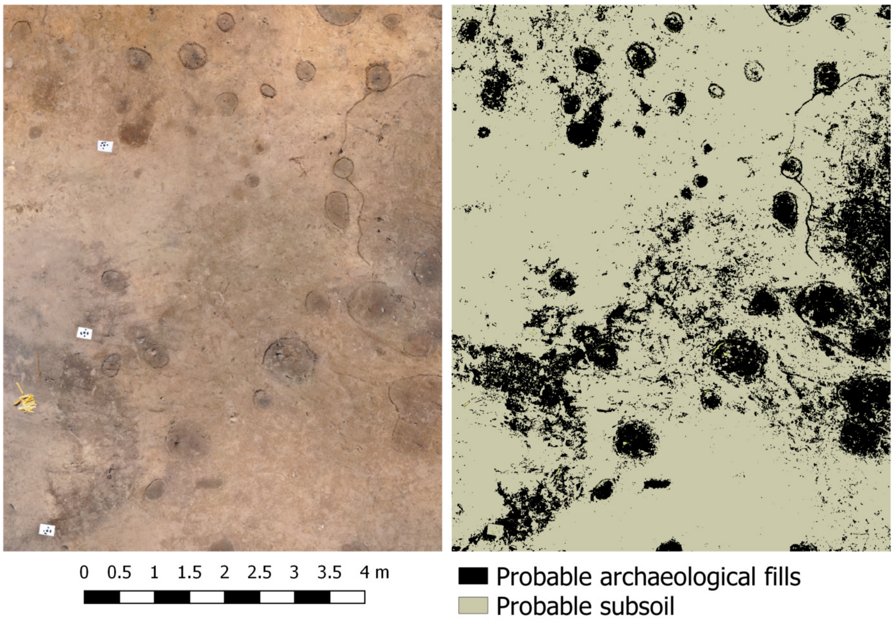

Figure 5.7: SVM-classifiers applied to horizontal photogrammetric documentation of an excavation plan. The black areas indicate the SVM evaluation positives of 'probable archaeological fill', according to the available training data.

5.6.4 Future improvements

To improve the discrimination of soil properties, better spectral and radiometric resolution than the 8-bit RGB images used here are required. By using cameras with a greater number of narrower bands across the visible and infrared parts of the spectrum the ability to distinguish elements of soil composition could be greatly improved (Verhoeven 2009). This can be achieved using either dedicated multi and hyperspectral imaging sensors or by adapting standard RGB cameras (Verhoeven 2009, Habel et al. 2012). Improving the radiometric resolution by using sensors with greater bit depth enables detection of finer gradations in tone and colour for each band, and should enable discrimination of subtler interfaces. Accuracy in classification could also be improved by employing more rigorous colour calibration of the source images.

Further experimentation is also required with the classification methods. There are many available options, including neural networks, logistic regression and decision trees. In addition, the approach adopted here uses purely spectral classification. This neglects physical texture, object shape and patterning that could also be used for identification. For example, sandy gravel on an excavated surface has a markedly different texture from clay. The data in the dense point cloud is often of sufficiently detailed scale to be able to do this, with point densities routinely exceeding 25 points per mm^2 (Stott et. al. forthcoming). This data is largely treated as redundant, and is discarded after the creation and decimation of meshes, however the ability to resolve soil texture at these scales has great potential.

5.7 Conclusions

Applying machine learning to rich 3D datasets enables archaeologists to apply their interpretations to large, complex datasets which would be infeasible to attempt manually. The proof of concept presented here is not about replacing the interpretative process with algorithms, rather, it represents an augmentation of these processes by extending them. Additionally, it provides quantitative measurement of uncertainty and heterogeneity which are problematic concepts to model using qualitative expressions in conventional data structures.

These data structures perpetuate 2D planimetric approaches, but the novel volumetric methods explored here afford great potential to exploit 3D data more fully. Without machine learning, segmenting and classifying these data into volumes becomes excessively time consuming and impractical and each benefits the other.

We envisage moving image-based 3D recording forward from being a passive means of recording representational data to becoming an interpretative tool, bringing together the spatial, temporal, qualitative measurements and evaluations of authenticity into one common model, where the difference between observed, interpreted and extrapolated data is always explicit.

The simplicity of this data structure makes it easy to visualise all those things, and that is really what makes a difference.

5.8 Bibliography

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6

Spatial Integration and Simplified Complexity through Object-Oriented Modelling

6.1 Introduction

The attention to data models in archaeology has steadily evolved during the first part of the 21st century. The technological developments of the 1980s and 1990s, which spawned the interest and digital preconditions for more efficient means of organising and managing data, have been met by an increasing preoccupation with the conceptual and semantic augmentation of data. Whereas data models, database management systems (DBMS) and technical limitations were the focus in the early years of digital archaeology, current developments focus primarily on the nature and interoperability of data itself. Primarily made possible by the presence of the Semantic Web and online ontologies, the attention to openness and accessibility of archaeological data have been promoted through a general aspiration towards the FAIR principles, as suggested in the ARIADNE project (Wilkinson et al. 2016; Aloia et al. 2017). Data should be made Findable, Accessible, Interoperable and Re-usable.

In this thesis, I have worked towards a realisation of a data model, which manages to integrate the spatial data produced during and after an archaeological excavation. This not only relates to the growing legacy GIS and CAD data of the "digital dark age", but the countless new data types connected to the increase of new types of documentation, particularly the increase of image-based 3D-documentation. The thesis seeks to address a concerning ambivalent attitude towards the importance of spatial data in archaeology, and how new technology and new methods align with the prevailing standards of archaeological documentation.

Paradoxically, spatial data does not integrate easily in a traditional archaeological workflow based on pro-forma lists of archaeological concepts of finds, features and contexts, particularly when things become digital. Granted, the advent of high precision GPS (GNSS) and total station measurements, which are comparable to traditional hand drawing, is a key asset to modern archaeological recording. However, rectified digital imagery, orthophotos, photogrammetry, Structure from Motion and 3D laser scanning pose new challenges to the way we manage, integrate, archive and search spatial data (De Reu et al. 2013, 2014; Forte 2014; Berggren et al. 2015; Dell'Unto 2016; Forte and Campana 2016).

Traditional archaeological practice has struggled with the conceptualisation and abstraction of a three-dimensional reality in a two-dimensional representation for decades. This struggle is further manifested by the eagerness of archaeologists in general to adopt, adapt and apply new technology, which may appear as an unbroken sequence, where the transition from one element to the next is almost indiscernible, while the extreme ends are distinctly different. To an extent, the consequences are something which is of little concern to most people, but archaeological practice may be severely detached from overarching research questions, conceptual conventions and even the archaeological methodological consensus. Meanwhile, the photo-realistic and geometrically accurate representation of excavations, provided by image-based 3D-modelling, create a confrontation with the role of documentation. It requires that we deal with levels of varying certainty or authenticity, in particular when combining 3D models or spatial hypotheses with recorded data, and necessitates consistent use of para- and meta-data to account for how data are created and derived - and to assign explicit meaning to an often implicit or even esoteric archaeological record.

Two important premises set the agenda for this theses from the outset: The Danish perspective, which incorporates a methodological tradition of sectioning and box-cutting of archaeological features, contrasted by the much more prevalent use of single context recording abroad (Carver et al. 2015). Secondly, in order to accommodate the infinite variation of excavation methods and traditions, it has been important to work towards a data model with a flexible data structure, which does not require or impose any particular registration system or terminology, but which allows for indefinite variation while retaining interoperability and transparency of how data are stored. In the process, data would ideally be subjected to an augmentation of their scientific potential and become searchable and consistent within this framework. In principle, a data model to manage everything, while simultaneously ensuring semantic and ontological links to enforce data interoperability.

In this final chapter, I propose a model which directly addresses the challenges of integrating spatial data, and demonstrate its functionality through the implementation of the Archaeo online database.

6.2 Why another data model?

The rationale for this thesis is, to a large extent, personal experiences gained from the application of new digital documentation principles at Danish research excavations; Skelhøj, Jelling and Alken Enge (Holst & Rasmussen 2013; Holst et al. 2013; Holst et al. 2018). These projects, which all prioritise digital field recording and documentation, clearly demonstrated an urgent need for efficient and flexible ways of managing increasingly complex spatial recording. At the same time, such large-scale projects, with national and international attention, also called for methodological developments, which not only advanced the level of documentation detail but, more importantly, established accessibility and interoperability of archaeological data - including spatial recording. As archaeology becomes increasingly interdisciplinary, and relies on scientific analyses (Kristiansen 2014), complemented by collaborations with geologists, biologists, chemists, physicists and anthropologists, the need for common frameworks, conceptual models and ontologies, facilitating data- and knowledge-exchange is vital.

More and more data are born into this world as digital bits, be it from digital surveying equipment or digital image-based recording techniques, inherently lacking an analogue counterpart. Complemented by many early digitisation projects, based on what is now legacy hardware and software, this poses a serious threat to data sustainability. As reviewed in chapter 2, archaeology has always been an early adopter of new technologies and methods, and eagerly applying software and hardware, which was not necessarily made specifically for an archaeological purpose, which is the case of most GIS and CAD software (Richards 1998; Lock and Pouncett 2017). However, the price for novel data analysis and management is also fragility, if not "kept alive". Not only is the digital archaeological record at risk of hardware failure and defunct software, but the inability to access and re-use data is a serious threat to the scientific foundation of archaeology. If data is not re-usable it is not reproducible, and if science is not reproducible it cannot be explicitly verified. This is an interesting conclusion in light of the role of reality-proximate 3D-documentation (chapters 3 and 4) and the promise of repeatability of otherwise non-reproducible archaeological observations. In addition, there is a vast amount of unpublished archaeological material and excavation reports, the "grey literature", which is not only a legacy but continuous source of inaccessible data (Aitchison 2010; Evans 2015).

Data models and repositories are essential in making archaeological data open and freely available for re-use, and the only way to combat data fragmentation, as seen through the ongoing works of projects like ARIADNE, Fasti Online and Pelagios Commons (AIAC 2004; Aloia et al. 2017). Of course, international archiving standards exist: for instance Dublin Core for metadata (DCMI 1995) and OWL for ontological modelling (W3C OWL Working Group 2012), which is also necessary to establish interoperability. It is, however, important to recognise that there is no single way to build a data model, repository or data visualisation framework, and scope, domain and focus should be taken into consideration and acknowledged in its design. It is important to emphasise that the data model and data structure proposed here are primarily meant as tools for field recording, immediate public dissemination as Open Data and aggregation of otherwise fragmented digital excavation data. It serves to fill a gap between the overarching conceptual reference models and ontologies, which allow high level data exchange, and the highly fragmented desktop field recording practices, which produces vast amounts of disconnected information (GIS shape files, spreadsheets, photos, desktop databases, ground control point lists and all the metadata used to describe this data). The case studies used in this thesis represent not only elaborate research excavations demonstrating particularly complicated conditions, but also highlight the value of basic excavation data harvested from available online sources. The data model is not necessarily a one-model-fits-all solution, although it is theoretically possible to include a comprehensive array of data types and represent most archaeological recording systems and conceptual frameworks.

6.2.1 Geographic Information Science

Every conceivable definition of modern archaeology has spatial data at its core. Having evolved as a discipline from the mere scientific study of prehistoric cultures by analysis of their material remains - in all their facets - the importance of context more than anything else permeates modern archaeology. The concept of contexts may be thought of, broadly, as the general circumstances surrounding a particular situation, or in this case the "find" (Harris et al. 1993; Roskams 2001; Carver 2009). Arguably, the concept of context relates to an entity with physical and temporal extents in the real world, and what follows is an archaeological preoccupation with three-dimensional spatial recording. However, if we were to assess archaeological methodology in its most usual form, three-dimensional would probably not be the first adjective to spring to mind. The extensive use of two-dimensional drawings to record both horizontal and vertical dimensions obviously relates to the recording traditions made possible by the available tools, which have traditionally been limited to pen and paper. However, it is exactly the relationship between the vertical stratigraphy and the horizontal extents which allows for chronological deductions that are vital to archaeological field work, and it is the inability to combine such two two-dimensional projections which is perhaps the biggest Achilles heel of modern archaeological excavation.

As discussed in chapter two, the role of three-dimensional recording has historically been recognized by archaeologists (Wheeler 1954; Andersen 1956; Ørsnes 1963) across different archaeological traditions, yet the visual representation of such recordings and the tools and methods to achieve such spatial abstraction have been surprisingly absent, despite rapid technological development. During the 1980s and 1990s, two-dimensional geographic information systems (GIS) steadily developed in archaeological application and use. Meanwhile the advent and availability of global navigation systems (GNSS/DGPS) led to a breakdown of the boundary between land surveyor and archaeologist, as intra-site and topographical analysis became one of the primary arguments for adopting GIS. Unfortunately, adopting GIS only encouraged the propagation of two-dimensional workflows from traditional recording principles, as the established excavation methodology was migrated almost directly to the new platform, presumably encouraged by the concurrent use of two-dimensional CAD, handed down by architectural recording and drawing conventions. This emphasis may be most evident through the adherence to single context recording, which seeks to counter the limitations of two-dimensional GIS, by reducing archaeological recording to manageable units (Harris 1979; Alvey and Moffett 1986; Harris et al. 1993; Pearson and Williams 1993; Kimball 2016). In this way three-dimensional complexity may be organised as a sequence of overlapping, horizontal two-dimensional representations or layers.

It is argued here that GIS has had two defining characteristics, which held back archaeological applications and methodological development. One was the lack of true 3D functionalities, which it sought to address primarily through various 2.5D approaches to spatial data (Wheatley and Gillings 2002; Lock and Pouncett 2017). The other was the lack of temporal management to account for spatial changes through time (Castleford 1992; Peuquet 1994; Karlsson 2001; Constandinidis 2005). Both of these factors have been emphasised historically by an apparent inability to even conceive how such approaches should be conceptualised for archaeological use. For instance, a stratigraphic sequence may be interpreted as either a spatial development of layers or contexts superimposed on each other, or a relative temporal development through time. ESRI, and its flagship ArcGIS did not introduce temporal functions until 2003, and then only as an extension rather than a core function (Johnson 2008), while these still remain absent as a core functionality among other mainstream desktop GIS solutions.

Another crucial point is the nature of Geographic Information Systems themselves. To some degree, they may be considered a “black box” (Wheatley and Gillings 2002: 2), where a significant proportion of the inner workings are not explicitly visible to the end-user, but are hidden behind a limited feature set of the user interface. Often spatial data may also be stored in closed-source, proprietary or binary file formats, which are not directly human-readable. Luckily, this tendency is being actively opposed by initiatives including the Open Geospatial Consortium (OGC), which develops and implements open standards for geospatial content and services, such as Geographical Markup Language GML and Well-Known Text (WKT) for representing vector geometry objects, rendering them both human- and machine-readable.

One significant limitation of GIS however remains its inability to work seamlessly with any data which lacks geometry. While, admittedly, most archaeological data has some spatial relationship, not all excavation data has an explicit geographic component, including for instance, lists of photos and administrative information about excavations and their results. This is inevitably very hard to manage in a purely GIS-solution without an extended data model and -structure built on top to manage complex relations and aspatial data. This is seen with IntraSIS (IntraSIS 2016), which builds on the ESRI ArcGIS software environment, and is one of the strongest arguments for why Geographic Information Systems will never be the quintessential archaeological tool, compared to a dedicated Archaeological Information System.

6.2.2 The Danish perspective

In terms of archaeology in general, the Danish perspective is particular, as it relies on a relatively unconventional branch of excavation methodology. It has a much stronger emphasis on a variety of spatial evidence, which is not confined to stratified, top-down or context-based recording. Instead, it relies extensively on vertical sectioning of identified archaeological features, “schnitt” or box-cuts as part of a consistent tool of hypothesis testing (Felding and Stott 2013). It arguably provides a cost-efficient ability to identify related features on large open-area excavations, sustained by the priorities of rescue- or contract archaeology.

Excavation practices in Denmark are, however, distinct, even beyond the methodological differences compared to, for instance, the UK (see chapter 2). In contrast to the increasing majority of archaeologies around the world (Carver et al. 2015), Danish archaeological excavations are politically and institutionally organised through a more traditional state-sanctioned affiliation with local museums. This is in contrast to the commercialisation of archaeology in most countries, where usually the cheapest tender amongst private companies wins the contract. For large-scale excavations in Denmark it is still the local contractor or landowner who pays the expenses for an archaeological excavation, following a budget approval by the Danish Cultural Heritage Agency. Each local museum is responsible for a geographic area in its immediate surroundings, roughly corresponding to the old parishes, hundreds (shires) and counties. The archaeological landscape has, however, changed drastically over the course of recent years, in response to ratification of the legislation "Museumsloven" of 2006, 2010 and 2012. This has led to stricter requirements for state-approved museums with archaeological responsibilities, and resulted in mergers to create larger administrative units. Today there are 27 such museums in Denmark, compared to 47 in 2007, and the trend appears to continue. The regulation dictates that each museum is obliged to conduct research, publish at least one monograph, 2-3 international articles and 5 Danish articles within a 5-year period. Of more immediate interest is the requirement to

> ".. ensure access to state-of-the-art excavation, measurement (GPS) and IT equipment to allow quality and efficiency in archaeological excavations and reporting thereof..." [translated by the author] (Slots- og Kulturstyrelsen 2016).

Furthermore, the museums are required to report to the Danish Sites and Monuments (Fund og Fortidsminder) and produce guidelines for archaeological recording, which must adhere to applicable standards; namely Danish Museum Documentation Standard (Dansk Museums Dokumentationsstandard, DMDS) (Wohlfahrt 2010). The DMDS is however limited to an XML-schema of only the most basic information needed for data exchange, and is of questionable value to act as a guide for archaeological fieldwork.

In general terms, no one museum or institution may excavate in another museum's area. However, the work force is generally very mobile, and many archaeologists are offered time-limited employment for one specific project or excavation at the time, which conceivably has an impact on the level of competition comparable to that of commercial archaeology. If the incentive to test out new, faster and more

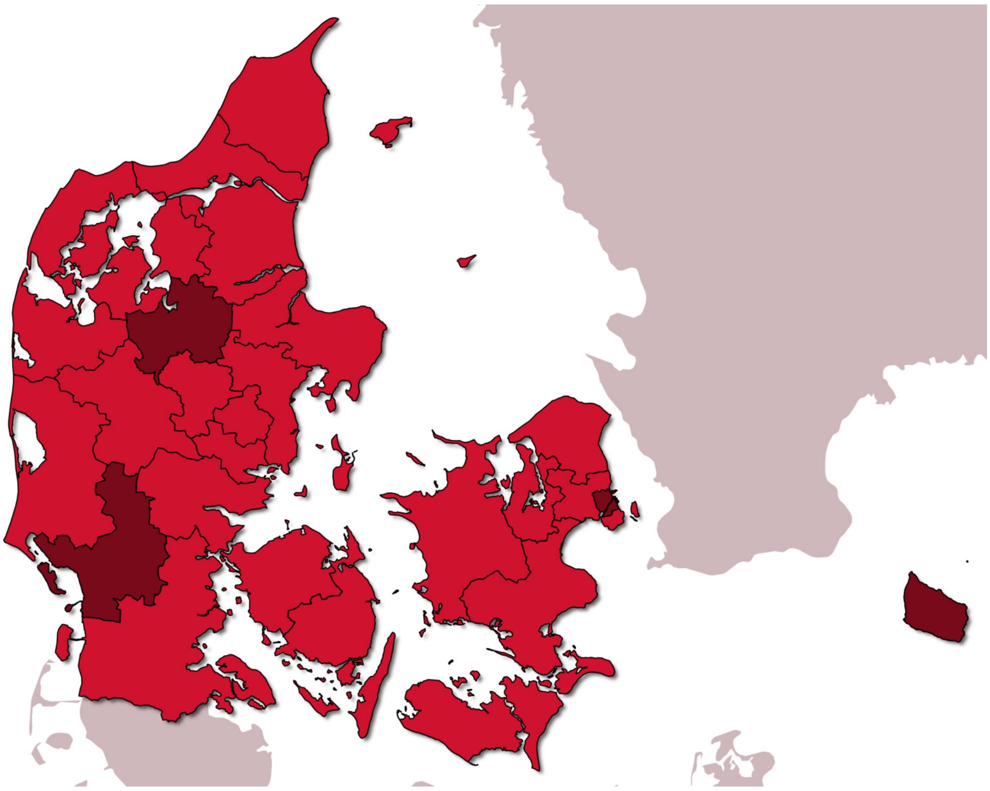


Figure 6.1: The Danish archaeological landscape of 27 excavating institutions (2018). Current members and contributors to the MUD archaeological database are shown in red; non-members in darker red. Source: www.udgravningsdata.dk and www.slks.dk.

efficient digital methods and applications relates to competition, Danish archaeology may be disadvantaged in that respect. On the other hand it is important to distinguish between competition of price and of documentation methodology.

What is, however, important to acknowledge is the level of autonomy each archaeological museum has in terms of excavation methodology and digital documentation guidelines (Jørgensen et al. 1980). Whereas Denmark was a relatively early mover for a national Sites and Monuments database (Hansen 1992; Christoffersen 1992), further development has been limited, and solutions for managing or accepting anything but basic, textual information about artefacts or objects, REGIN (Eaglestone et al. 1996), and site-level administrative information about excavation activities, has so far not been pursued. At the moment, the growing amount of digital data and the lack of an efficient national infrastructure is a serious concern (Løvschal 2016; Møller 2016). As a consequence, a group of museums formed the grass-root movement of MUD (The Museum Excavation Database) in 2007, as a privately funded initiative supported by almost all the archaeological museums in Denmark (MUD 2014). MUD accepts all the general textual outcomes of an archaeological excavation, including lists of finds, features, drawings, photos, and it enforces standardised thesauri and cultural period definitions. However, following 10 years of use, it does not yet support any type of GIS or digital spatial data, although plans have been made, and abandoned, in expectation of the promises of the new, national database SARA (Slots- og Kulturstyrelsen 2015). Instead, the museums have been forced to come up with individual solutions for storing and handling the vast amount of GIS-data, primarily proprietary MapInfo files, consisting of separate tables or layers for trenches, features, finds etc. Luckily, the introduction of RTK GPS/GNSS for efficient field recording has lead to some level of standardisation (Precht 2007; ArkDigi/MapDigi 2015), as most museums have used the ArkDigi/ArkMap software to convert measured points into polygons. This has unfortunately also resulted in the departure from 3D point data to two-dimensional GIS polygons. Meanwhile, original data as well as derived data is almost exclusively stored in local file systems and shared network drives, according to the individual guidelines of the museum (or archaeologist).

In 2013, as part of a general migration initiated by the National Survey and Cadastre of Denmark, Archaeological IT at Aarhus University offered to assist museums in re-projecting archaeological GIS datasets from the old European Datum 1950 map projection onto the newer WGS84/ETRS89. The transformation process was impeded by limitations to the spatial reference systems built-into MapInfo, which resulted in inaccuracies of several meters, if not done according to correct specifications. Nonetheless, it provided a unique opportunity to identify the different data management procedures of various museums, but also allowed for a quantitative assessment of the amount of concurrent and legacy GIS-data which was building up. Table 6.1 shows the expected, actual and converted data from the participating 7 museums of the total of 27. While the actual count was lower than expected, mainly due to redundant and replica data, what is perhaps more critical is the fact that it was only possible to convert 71% of the files. The remainder used local coordinate systems or were otherwise impractical to re-project without extensive processing, clearly demonstrating the growing legacy of digital “dark-age” data, which is at risk of being lost because of its limited spatial integration. Although many factors are at play, the fact that 26% of the museums by 2013 had produced over 100,000 GIS datasets, and 5 years later there is still no infrastructure for spatial integration of archaeological datasets, it is clearly a giant undertaking to secure this data for the future.

On top of the legacy GIS-data, museums are increasingly accepting 3D-documentation, which has so far been left outside of most documentation guidelines, not least because of the storage required and thus the cost of image-based 3D recording. How does data acquired for 3D documentation align with the general consensus to keep primary field data for posterity? And how does the massive increase in

Table 6.1: GIS file count during the 2013 Coordinate Transformation Project by Archaeological IT, Aarhus University.

Institution	Expected	Actual	Converted
Moesgård Museum	27,000	13,000	10,900
Museum Østjylland	14,500	23,437	21,123
Vejle Museum	9,917	9,917	1,870
Nordjyllands Historiske Museum	19,143	20,000	20,000
Museum Sønderjylland	28,000	28,000	12,000
Museet på Sønderskov	11,000	4,800	3,300
Thisted Museum	19,657	3,174	3,150
Total	**129,217**	**102,328**	**72,343**

digital photography interfere with the usual procedures for keeping lists of photos, not to mention the limited three-dimensional support by mainstream geographic information systems? At the same time, we lack a fundamental methodological discussion regarding the documentation end-goal. Currently, most archaeological 3D applications entail image-based Structure from Motion 3D documentation, mainly as a tool for generating two-dimensional orthophotos, which may be used as an equivalent to traditional two-dimensional drawings, and almost all the extra detail and extra information provided by the technology is discarded due to conceptual challenges and a lack of methodological development.

Generally speaking, development of methods in Danish archaeology primarily takes place at the archaeology departments at Copenhagen and Aarhus Universities, and new digital ideas are either mediated through university-involved research excavations or as new archaeology graduates gain employment. For example, the excavation at the Bronze Age barrow Skelhøj (Holst & Rasmussen 2013) in 2001 onwards was the first Danish project to employ an entirely digital documentation process, working with GIS from rectified, georeferenced and vectorised digital photography (Johansen 2003; Madsen 2003a). This particular project was a collaboration between Aarhus University, the Danish National Museum and the local museum Museet på Sønderskov, and was an eye-opener in terms of realising the importance of having a conceptual framework and data model workflow that support new types of data, new archaeological constructs and new branches of field recording methods. This was where we first introduced the new concepts of event-driven documentation (chapter 4.3.1) to deal with an excavation that spanned over several years. Each year going deeper into the barrow meant dealing with overlaps, and re-cleaning of previous years sections meant that the individual turves changed in extent and appearance. A growing concern was how to retain the origi-

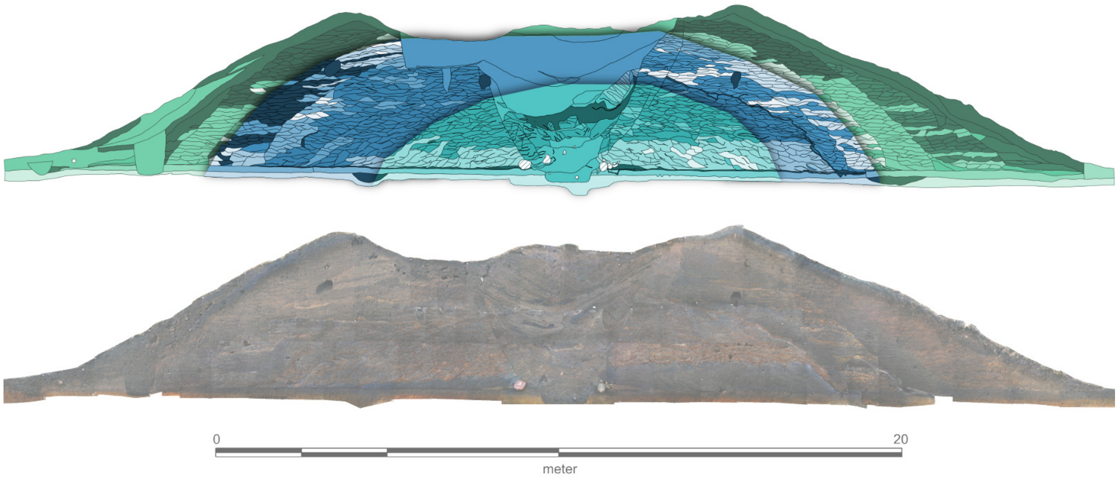


Figure 6.2: The main vertical section through the Bronze Age barrow Skelhøj. Overlaps of three consecutive excavation campaigns (illustrated here in separate colour schemes) were managed digitally by the use of Documentation Events and Data Collections to ensure that no primary data was edited or deleted when merging the individual datasets. Vectorisation was performed using 2D rectified photos (bottom mosaic).

nal documentation when connecting documented turves from one year to the next, and we would occasionally end up simply free-hand editing to make the sections fit each other (see fig. 6.2).

New conceptual entities or "Documentation Events" helped separate different spatial representations, in which no data was ever deleted and modified. Instead, separate Documentation Events would act as containers for edited or derived representations. Another important lesson from working with Skelhøj was learnt by investigating the building principles of Bronze Age barrows. We wanted to excavate and document curved, vertical sections to be able to identify radial structures in the layout of the individual turves (see fig. 6.3 and fig. 3.1). This allowed for the identification of individual sections with distinctly different soil-composition within the barrow construction, assigned to individual Bronze Age building teams and different areas of turf-collection. This of course meant that we had to deal with pseudo 3D documentation, as the technology had not yet matured enough. But luckily all primary data and photos have been kept in order to take advantage of technological progress, and potentially re-work the documentation at a later point.

At the time of writing, the cultural historical institutions of Denmark are waiting for the new national database SARA, which promises to replace the ageing Sites and Monuments database and REGIN for artefact recording and other domain-specific systems across institutions in a common data model. Development was

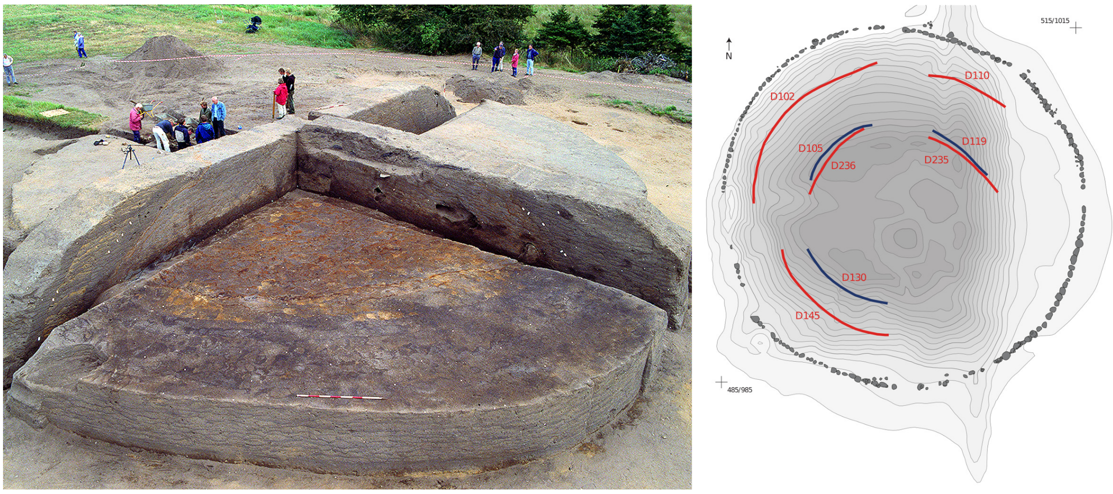


Figure 6.3: The curved sections and surfaces in the Bronze Age barrow Skelhøj used to record and identify radial structures challenged the spatial conceptualisation of digital recording. (Holst & Rasmussen 2013).

started in 2011, and it was scheduled for release in the beginning of 2016. Unfortunately, aligning the requirements and expectations of the very different institutions has been challenging and, even though a common conceptual model was reached in 2011, it has proven difficult to realise, despite building upon an Axiell Collection standard system. Even more concerning than the two-year delay is the fact that spatial data was never part of the core requirements to the system, but considered a nice-to-have feature.

The long wait, and uncertainties as to what to expect of the new system has had consequential influence on digital initiatives over several years, where most development, including MUD, has come to a standstill while waiting for SARA.

6.2.3 So why yet another data model?

The primary justification to pursue another data model relates to how spatial data so far has been paradoxically neglected as an integrated part of digital excavation documentation, despite the discipline having geospatial location at the heart of field recording. Furthermore, almost any archaeological research question requires access to combined geo-location, spatial as well as classification data. The most common question is: “What is found where?“

As demonstrated in the previous chapters, it is essential to record and retain a historical dimension of data. This means that we need a data model to ensure that no data are ever deleted or modified: effectively time-stamping all generated data – recorded or derived – with meta- and para data related to when, who and what created this iteration of data. This has the benefit of vastly reducing the need for handling redundant and derived data separately, and allows for distinguishing efficiently between original observation-data, interpretations, models or hypotheses and various combinations thereof.

It is also important to distinguish between administrative databases and research tools, where the majority of the currently available services, including Sites and Monuments records, are primarily used for cultural heritage management purposes, rather than offering the desired level of detail to act as a research tool. Also, considering the very dispersed and autonomous nature of datasets in Danish archaeology, it is imperative to ensure the ability to search across archaeological sites, as well as archaeological institutions and individual repositories. At the same time a data model needs to be sufficiently dynamic to accommodate the autonomous nature of Danish archaeology, and not to attempt to impose a one-solution fits all strategy.

6.3 An Archaeological Data Model...

In chapter 3 I discussed the use of 3D models in archaeology, whilst refraining from pursuing a semantic or philosophical debate about what a model actually is. In particular when it comes to 3D recording or reconstruction, the modelling aspect is extremely diffuse, and I emphasised the necessity of proper meta- and para data to address any concerns of validity, conjecture or authenticity of the archaeological documentation. Arguably, even many archaeologists do not agree on the definition of a model, which I primarily use to describe the hypothesis and the relation between the observation and interpretation; not unlike the concepts introduced by New Archaeology of the 1960s (Clarke 1968, 1972). On the other hand a model may simply be:

> "a model is a simplified representation of some sort of reality" (Orton 2004)

which I would argue is not the case when it comes to 3D models derived from 3D image-based recording or human-modelled virtual reconstructions. Gillings (1999:250) discerns between virtual reality models representing existing remains of an archaeological site and models without any "tangible referent" which cannot be tested against reality. The latter, "imperfect" representations can be used as catalysts for exploration and interpretation. Goodrick and Gillings (2000:44) object to evaluating the authenticity of such models, unless they refer to visual representation as well as process, biography and embeddedness, which is the case here. Authenticity has nothing to do with how 'lifelike' our photo-realistic 3D models are - that is for public dissemination, where manipulation is allowed (Eiteljorg 1998, 2000; Wittur 2013). Instead the validity and authenticity of the model relates to either the degree to which data fits a hypothesis (Hodder and Hutson 2003:239) or to what extent it is derived or generalised from an "original" dataset.

In terms of models of the past, it comes down to the extent to which the contemporary static phenomenon of the archaeological record may be used to draw conclusions about events in the past. Madsen (1995) argues that there is no set of rules, as suggested by Binford (1977), that allows us to account for all successive transformations between the past and the present, or how plausible the meaning you "read" from the archaeological record is (Hodder 1999). Madsen instead suggests the use of models as a continuous dialectic process to iterate between models of fact (the archaeological data) and models of theory (the mental construction of the past). When Dwight Read (1990) proposed this research process of comparing data models (ModelD) with theoretical models (ModelT), he did so as a strict formalised mathematical model which fits a processual theoretical view, yet it needs not be. Madsen points to how it applies to more informal modelling as well, and resembles the intrinsically bilateral workflow of archaeologists, who arguably do not only try to construct theoretical models that reflect data. They may also manipulate or generalise data to fit a data model, which is then used to promote or reject a theoretical model. The most important challenge is to provide explicit information about dialectic research process and negotiations between hypotheses and raw data. It is very useful to apply this line of methodology to the dichotomy of reality-proximate 3D recording and 3D models or reconstructions as those discussed in chapter 3.

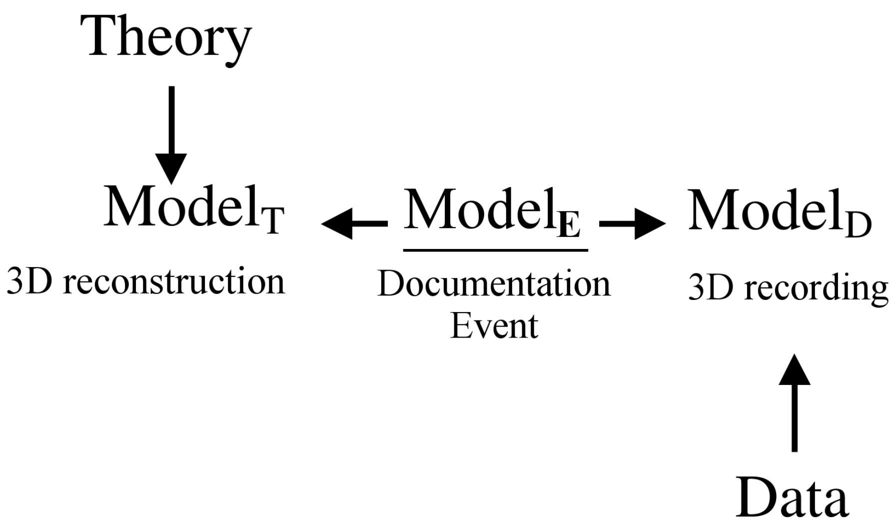


Figure 6.4: A schematic diagram showing the relationships among theory, models and data. Modified to model a complex spatial conceptualisation. Based on: Read 1990.

Table 6.2: Levels of abstraction between reality, model and data representation. Adjusted to include DBMS. Originally by: Peuquet 1990:252.

Definition	Description
Reality	Phenomenon as it actually exists including all aspects, which may or may not be perceived by individuals.
Data model	Abstraction of the real world which incorporates only thos properties thought as relevant to the specific domain or the application at hand, usually a human conceptualisation of reality.
Data structure	Representation of the data model often expressed in terms of diagrams, lists and arrays designed to reflect the recording of the data in the computer code.
Database	Representation of the data in a database management system (DBMS).
File structure	Representation of the data in storage hardware.

In figure 6.4 the original model has been adapted to demonstrate its applicability through a ModelE for epistemological events. Most importantly it allows us to pinpoint three crucial elements in an archaeological data model or -structure: the data model, the data theory and - not least - the explicit negotiations between them. The natural solution is through an extensive use of meta-data to describe data model and theoretical model, and to describe how data and knowledge flows between them.

The layer of abstraction between the observer's interpretation of reality according to his or her skills and experiences was also discussed in chapter 3, and this defines how spatial data models are created and used. In practice, any archaeological recording goes through a process of generalisation, and is defined by the more or less deliberate distinction made by the archaeologist about which observation is significant and which is not.

Looking at table 6.2 we may be tempted to ask where the archaeological knowledge actually resides, if we merely account for our documentation through a hierarchy of abstractions between reality and the derived data. By these definitions, the data model, data structure and database itself are the primary targets of the research presented in this chapter.

Meanwhile, a digital data model is defined by a set of rules, to which any recording must also adhere. In GIS we are often limited to a set of geometric rules such as the basic primitives: points, lines and polygons in addition to georeferenced raster representations, while in archaeology we are often dealing with entities which are dynamic and spatio-temporally extremely complex, and which have properties which cannot be represented adequately using conventional vector and raster data models. This may be described as a *semantic gap* (Mennis 2003:456) in GIS database representations between the user's conceptual model of a given application domain, in this case archaeological contexts, features and artefacts, and the representation of that conceptual model within GIS.

A significant amount of research has gone into addressing this semantic gap and its related issues by the representation in GIS-databases through object-oriented modelling (Tschan 1999; Wheatley and Gillings 2002; Worboys et al. 2006), although attention has mainly been focussed on the representation of complex geometry as an extension of the vector data model, without focusing explicitly on the conceptual representation. Thus none of the mainstream GIS solutions currently provide any real solutions for spatial conceptualisation of the "fuzzy" borders in the soil which archaeologists deal with every day, nor easy access to object-oriented data management capabilities for the integration of archaeological classification.

As we shall see in the following discussion, object-oriented modelling may very well be a sensible solution, although it also means moving archaeological spatial recording out of the proprietary sphere of existing GIS/CAD solutions. Furthermore, it means drawing upon the field of ontologies and principles of cognition. The term ontology is used to describe a set of concepts and categories in a subject area or "domain", their properties and the relations between them. It is a formal declaration, usually accompanied by a standardised vocabulary. Thus it is used to formalise how entities in the archaeological domain may be generalised and symbolised – it is a specification of documentation (Cripps et al. 2004). Yet, interestingly, formalisation and generalisation is at conflict with the increasing use of image-based 3D modelling, which seeks to provide the most reality-proximate representation of the archaeological situation – devoid of predetermined conceptual models or ontology-driven geographic information. What does, however, become prevalent are discussions of cognitive categorisation and "top-down" versus "bottom-up" information processing, which were considered in chapter 5 (Lucas 2015:18).

I employ the term "archaeological data model" to describe the representation of an archaeological conceptualisation of reality (see table 6.2), including the properties and relations needed to describe primarily archaeological entities. This includes any type of data collected before, during and after an excavation, as part of quantitative measurements (GPS, total station, geophysical prospection, documentation imagery, scientific analyses) as well as the more qualitative archaeological interpretations and descriptions.

6.3.1 ...for complex spatial data

The preceding chapters have served to demonstrate the fundamental challenges which face us: namely the inherent disassociated and dichotomous nature exhibited by different excavation recording data types: *Analogue or digital*, *vector or raster*, *horizontal or vertical*, *2D or 3D*, each appearing independent of the other, yet part of the same dataset. For instance, the effects of parallel series of data are abundantly clear in the Danish open area excavations where thousands of postholes are systematically sectioned by box-cut, drawn and described (Felding and Stott 2013; Larsson et al. 2015). Besides a reference to the GPS-derived excavation plan, these vertical sections rarely exist as an integrated or even digitized part of the documentation. This is in part due to the inherent limitations of GIS, which do not provide easy out-of-the-box solutions for managing horizontal and vertical representations in one common spatial solution. This is a paradox, considering the amount of time and resources which go into sectioning postholes, and the extent to which the vertical sections of postholes are considered an important source for hypothesis testing and the identification of large-scale structures and stratigraphy. The detailed classifications of finds and features, which end up in GIS, are furthermore intrinsically restricted by the unstructured or flat data management capabilities of mainstream GIS applications, and generally only supplemented as separate external lists of additional classification information.

In the original project title, the term “complex spatial data” was deliberately kept extremely broad. It is an acknowledgement of the fact that technological developments are continuously and increasingly delivering new data types, new data formats and new data standards; not least in dealing with spatial data, legacy and state-of-the-art. Take, for instance, the affordability of image-based 3D recording and accessibility of 3D printing, mirrored by advances in virtual- and augmented reality for games and dissemination, and the explosion of map-enabled webpages and freely available geodata. While the focus of this thesis has been on image-based 3D recording, it would be very difficult to argue that this particular technology will remain unchanged in the foreseeable future. Thus any proposed new data model or structure should take this into account and seek to be as dynamic and extendable as possible. The following is therefore not an exhaustive list of spatial data types currently in use, but is based on the types of spatial data which are expected to be produced as part of everyday contemporary archaeological fieldwork.

Today, a common conception among archaeologists is that vector representations are superior to raster representations, or at least that they lie closer to our goal of documentation. This almost certainly is a testament to the historical digitisation process of archaeology. Early actions were aimed at scanning old excavation plans with the purpose of georeferencing them, and more importantly, vectorising to allow interpretations and classifications to be embedded alongside the geometry. This crucial element is required to do any spatial queries or thematic

Table 6.3: Various common spatial data types, their source and use in archaeology.

	Spatial type	Used for	Primary source
VECTOR	Points (2D/3D)	Finds, levels, ground control points	GPS/TS surveying equipment
	Point clouds (3D)	Pseudo-surface visualisation, buildings, large scenes	Laser scanner, SfM software
	Lines/polylines (2D/3D)	Graphical element or loosely defined boundary	Vectorisation (GIS/CAD/GPS)
	Polygons (2D)	Finds, contexts, features, trench borders	Vectorisation (GIS/CAD/GPS)
	TINs (2D/3D)	Tessellated points to generate a continuous surface	GIS processing
HYBRID	Meshes (3D)	Textured 3D models, orthophoto-generation	SfM software, 3D software
	Voxels (3D)	Volumetric models	SfM software, GIS processing
RASTER	Discreet data (2D)	Land use, predictive modelling	GIS processing
	Continuous data (2.5D)	Elevation, geomagnetic and resistivity surveys	Remote sensing equipment
	Rectified orthophotos (2D)	Plan and section drawings	(2D) photogrammetry software
	Projected orthophotos (2D)	Plan and section drawings	SfM software

mapping, and has been the main selling point for many archaeological implementations of GIS. Incidentally, the advent of nation-wide LIDAR scans in later years, has reintroduced the value of raster representations to archaeology, although now as continuous data to be mapped, rather than simple paper scans. LIDAR data is thus visualised using hillshade processing to show all minute earthworks, such as ploughed-out burial mounds and ancient field systems, which are otherwise difficult to detect. Meanwhile discrete data is used in raster representations for everything from predictive mapping to geophysical prospection to least-cost paths and viewshed analyses (Wheatley and Gillings 2002; Conolly and Lake 2006; McCoy and Ladefoged 2009).

As discussed in chapter 5, a polyline in 3D space is conceptually difficult to use as a spatial representation of archaeological entities, or as representation for any three-dimensional object for that matter. The two-dimensional nature of a line is in conflict with the 3D space in which it is placed, and only makes sense as a wireframe model, which in a formalised manner serves to represent, edges, faces or facets of more complex geometry. Likewise, polygons only exist in a two-dimensional space, as tessellation or triangulation are needed to instantiate surface between the individual vertices of the polygon. The extensive use of polygons as archaeological representations in GIS is thus out of alignment with the concept they serve to convey, in particular when the ambition is to visually conceptualise a three-dimensional observation.

6.3.2 Storing and managing spatial data

Of the different spatial data types provided by GIS, vectors and rasters are by far the most used. To recapitulate, vectors are finite straight-line segments, defined by their endpoints (Worboys 1995) which are well suited for representing an entity-based data model; i.e. one entity in the GIS database relates to a vector

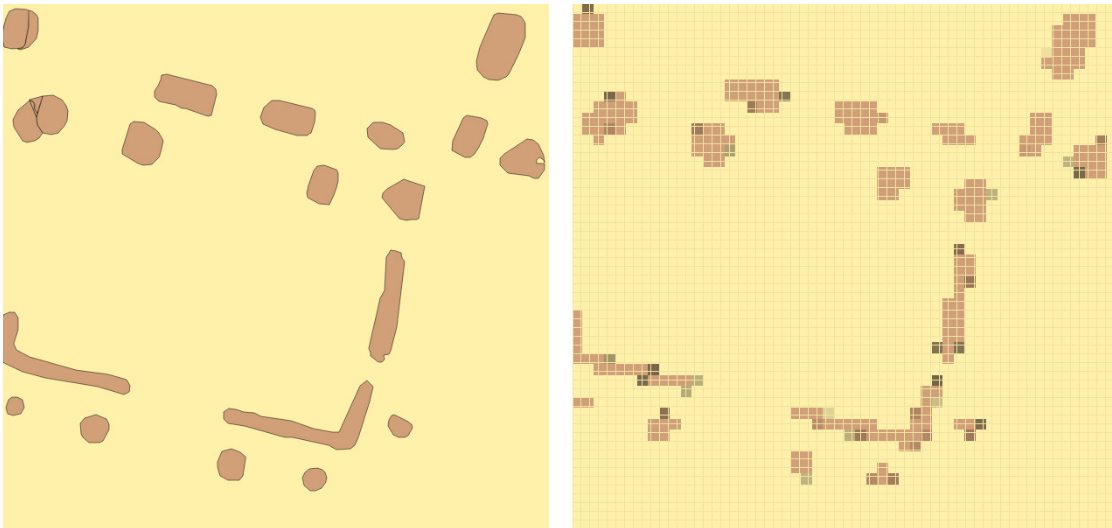


Figure 6.5: Vector and raster representations. This example shows postholes belonging to Viking Age building in Jelling.

geometry (point, line, polygon). Rasters are structured arrays or grid-cells, usually referred to as pixel, and may hold values which translate in the colours, elevation or other continuous values. The two representations are used to represent different views of reality, but more important is how they relate to, and integrate with, other data. Raster structures rely on an intrinsic database for representing space, whereas vector structures are formed by a more complex and structured database, where spatial and attribute data are related but stored separately (Merlo 2016:35) (see fig. 6.6).

For the more complex spatial data types, which are only partly supported by GIS other structures apply. Voxels (chapter 5) may by structured in an array as normal rasters, but as a three-dimensional array. Basically this means that a normal raster image (for example a multi-paged tiff or geotiff) may be used to store its information. A 3D mesh would usually rely on a combination of vectors and rasters; points to represent vertices, triples to represent the individual mesh faces, and triples to store vertex-colour, face-colour or texture-coordinates for an associated raster image.

As mentioned, the vast majority of GIS data in archaeology exist as individual, proprietary GIS-files. It is possible to distinguish between the widely used, proprietary standards, predominantly ESRI Shapefiles or MapInfo Tables and open formats like GML and GeoJson, and fortunately import and export functions are usually supported by any GIS application. However, one actual common spatial standard for GIS, CAD or 3D exchange has never emerged. "Attempts at defining a universal data model for geospatial data have been made (for example the Spa-

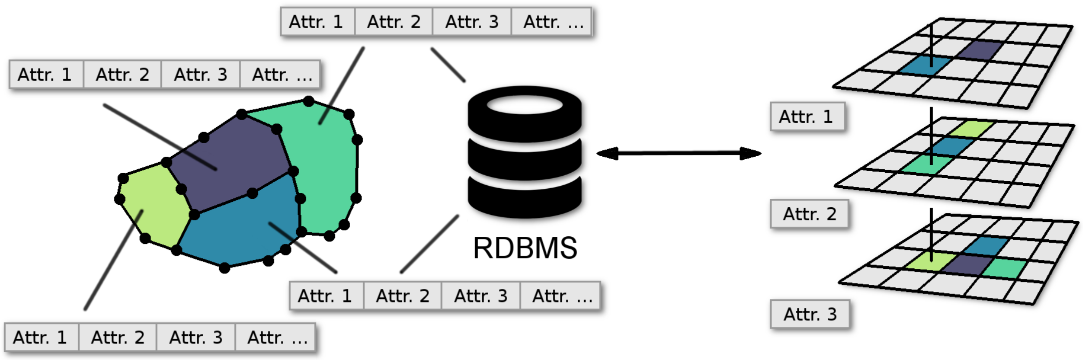


Figure 6.6: Vector or entity-based spatial data types (left) have access to more complex and structured database compared to the intrinsic values stored in a raster representation (right). Based on: Burrough 1996.

tial Data Transfer Standard (SDTS), but have not achieved widespread adoption. As a consequence, it is not possible to speak of 'geospatial data' as a single type of information that can be handled by multiple, functionally equivalent applications and formats." (McGarva et al. 2009:5).

It is important to emphasise the importance of open and transparent spatial data. For many desktop GIS users, what happens behind the frontend in terms of individual vertex coordinates, projection transformations is often obscured by the priority of user-friendliness, as it should be. For archiving purposes explicit information is required however, such as coordinate reference system, geometry (e.g. point, polygon, line), attribute fields and, for rasters, location/rotation/scale, source elevation model, colourmap, etc.

A fundamental precondition for managing and archiving spatial data is that data adhere to a minimum of guidelines for best practice to ensure a general level of interoperability. A good starting point is the Guides to Good Practice developed by Archaeology Data Service (ADS) and Digital Antiquity (tDAR). These guides emphasise the principles of how digital data produced from archaeological investigation should be managed and archived in a digital format. Such an approach should avoid costly re-digitisation in the future while ensuring maximum accessibility and re-usability of the data. Digital archiving also preserves the functionality of complex datasets such as GIS, CAD, and relational databases that simply could not exist outside of a digital medium (Archaeology Data Service 2015). From an archival viewpoint, storing spatial data in a ASCII markup language like GML offers the desired transparency of data and independence of proprietary software, while GeoTIFF (Ritter and Ruth 1995), with its public domain metadata standard, offers a safe option for archiving raster data. Since 2016 the Guides also include recommendations for 3D data, which take the same approach to data, avoiding

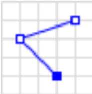
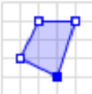
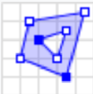
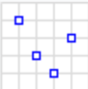
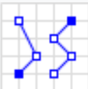
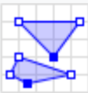
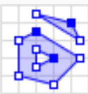
Geometry		Well-Known Text (WKT)
Point		`POINT (30 10)`
LineString		`LINESTRING (30 10, 10 30, 40 40)`
Polygon		`POLYGON ((30 10, 40 40, 20 40, 10 20, 30 10)`
		`POLYGON ((35 10, 45 45, 15 40, 10 20, 35 10)` `(20 30, 35 35, 30 20, 20 30))`
MultiPoint		`MULTIPOINT ((10 40), (40 30), (20 20), (30 10)`
		`MULTIPOINT (10 40, 40 30, 20 20, 30 10)`
MultiLineString		`MULTILINESTRING ((10 10, 20 20, 10 40),` `(40 40, 30 30, 40 20, 30 10))`
MultiPolygon		`MULTIPOLYGON (((30 20, 45 40, 10 40, 30 20)),` `((15 5, 40 10, 10 20, 5 10, 15 5)))`
		`MULTIPOLYGON (((40 40, 20 45, 45 30, 40 40)),` `((20 35, 10 30, 10 10, 30 5, 45 20, 20 35),` `(30 20, 20 15, 20 25, 30 20)))`

Figure 6.7: Vector data types stored in spatial enabled database using OGC standards and Well-Known Text (WKT). https://en.wikipedia.org/ wiki/Well-known_text

proprietary binary formats to ensure that data is readable as text. Formats as Stanford PLY and Wavefront OBJ file formats provide this for 3D.

These guidelines however relate to archival file formats for file storage and do not take into account how data behave when stored in a database. While much work has focused on 3D geodatabases, most have focused on their analytical potential rather than their archival suitability (Zlatanova 2006; Abdul-Rahman et al. 2010; Breunig and Zlatanova 2011) For this we may instead rely on the Open Geospatial Consortium (OGC 2018) library for vector data and GDAL library for raster geospatial data. However the internal database storage is organised, a spatial enabled database has both built-in functions and methods for indexing spatial queries as well as transactions using OGC standards, of which Well-Known

Text (WKT) is perhaps most interesting (see fig. 6.7). It provides basic well-known text, transparent, human-readable and efficient storage for vector data.

As for raster storage in databases, it is technically possible to integrate rasters as some textual representation in the database (RGB values in an array), but the practical justification is not apparent. We would rarely need to query by subsets of a raster dataset, and it has a significant impact on database performance - and filesize. On the other hand, most platforms handle even large raster very efficiently using standard image libraries and file formats (tiff, jpg, gif, png etc.).

6.4 Modelling excavation data

6.4.1 The relational database and archaeology

Archaeological recording hinges on a relational or hierarchical paradigm, where finds and features appear as part of larger structures or are attributed certain characteristics. This is most likely why the majority of archaeological databases, at least in the early days of computational archaeology, have been based on relational database management systems (RDBMS).

The structure of a relational database is very simple, which is also what makes it inherently versatile and powerful. In essence it is a collection of tabular relations, where data is structured as a set of rows (tuples) in a table, with a list of values in columns - one for each attribute. Individual tables or entities are interrelated by unique primary- and foreign keys, commonly by one-to-many relationships, however, once a table structure (attributes) and entity-relationships are defined, changing them becomes exceedingly complex, proportionate to the amount of data it holds. It is therefore superior for enforcing referential integrity between tables, and minimises redundant data, while equally inflexible for dynamic alterations to the data structure.

The use of archaeological numbering systems as an integral part of how we conceptualise archaeological recording was discussed in chapter 4.3.1, and is a necessity to systematically manage units of an archaeological excavation in a simple, logical, easy readable and retrievable way (Roskams 2001:112). The simplest perceivable way is naturally by tabular records, keeping lists of ordered finds, contexts, photos etc., which works equally well from a conventional analogue pen and paper approach or a digital spreadsheet equivalent. By extension, the simple next step is to relate each record in a list to another record, in another list. At first glance, much of archaeology can by explained and described by simple one-to-many relations; i.e. any number of finds may belong to (be found in) one specific context, while a single find cannot belong to more than one context. Or can it? What happens when the complexity increases and we start to look at contexts as part of larger structures? At that point do individual finds not only belong to a single context, but a larger complex of many-to-many relationships. The same goes for almost any relations in an archaeological conceptual data model; photos, drawings,

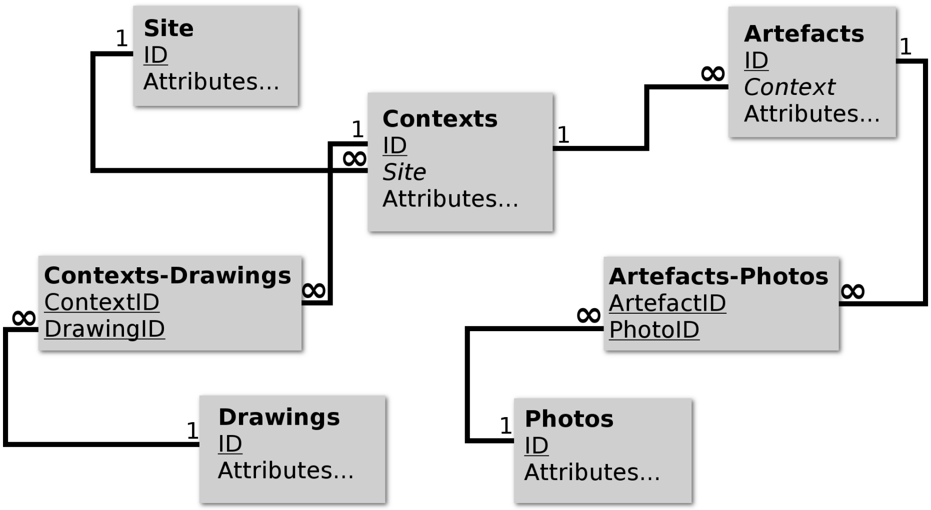


Figure 6.8: An example of a simple relational database model, comprised of one-to-many, or many-to-may relationships between tables using link-tables. Entities and relationships between tables are defined uniquely by primary- and foreign keys (underlined / italic).

features, finds all interrelate in complex relationships. This is not to speak of the complex relations used to model a stratigraphic sequence through, for instance, a Harris Matrix, by a series or hierarchies of superimpositions (Harris 1979, Roskams 2001:153).

In the late 1980s the inherent complexity and diversity of archaeological data had become a growing concern. Realising that flat files and hierarchies were too simple to provide a basis for the description of the complex archaeological reality, it became a priority to investigate solutions to counter the increase of ad hoc solutions (Madsen 1993).

Originally developed by Stead and Clark at the Scottish Urban Archaeological Trust (Stead 1988), the Integrated Archaeological Database (IADB) (Rains 1985, 1989) was developed as a computerised integrated database to record and help with the analysis of several large excavation projects. Initially, this included stratigraphic analysis, finds and context recording and was one of the first digital solutions for managing single context planning. Further development was resumed by Rains who brought it to the York Archaeological Trust in the late 1990s. What made IADB special was its integrated capabilities, allowing spatial management, i.e. vector excavation plans, alongside the textual classification (Stead 1988). Over time, the IADB aided in the evolution from an ad hoc, “digital workbench” or a “computerised desktop” to a web-based application, while Stead went on to develop definitions for the CIDOC conceptual reference model (Doerr et al. 2007, 2011).

In 1993 Madsen and Andresen at Aarhus University received funding for a three-year project from the Danish National Research Foundation for the Humanities, to realise their IDEA – the Integrated Database for Excavation Analysis (Andresen and Madsen 1996a). The core system was implemented in a relational database management system, and at the time Microsoft Access was the only viable solution which could model and handle the complexity. Common relational database systems were limited to one-to-many relationships, but Microsoft Access offered capabilities for handling many-to-many relationships, in a low cost, standard PC environment. They proposed a conceptual model consisting of three universal entities to hold all excavation information; Layers, Objects and Constructs supplemented by entities for Photos and Drawings in an entity-relationship model (Andresen and Madsen 1996a, 1996b).

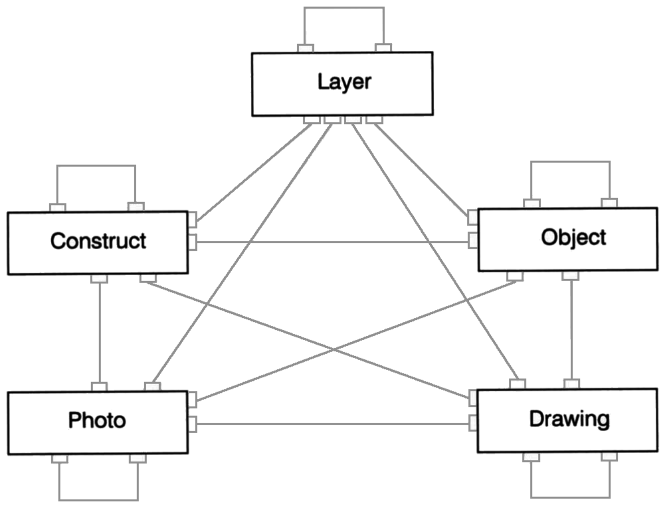


Figure 6.9: The IDEA data model (Andresen and Madsen 1996a).

The IDEA data model is an example of a solid data-model and -structure, which is aligned with a conceptual model for how archaeologists view the world. However, as the project progressed into the following ArchaeoInfo database (Madsen 2003a), more and more issues arose. Firstly, the implementation of IDEA itself was built around its conceptual model and, even though the model could hold and describe any conceivable entity or relation of the real world, all archaeologists may not agree on the core concepts of archaeology. For instance a “Layer” or a “Feature”, which is not necessarily identical or synonymous to what others would characterise as a “Context”. A “Context” is perhaps better described as a “Construct”, and so forth. Even though the philosophy behind IDEA was to reduce everything to the most basic and minimal units of observation, in reality no two archaeologists necessarily agree on what would otherwise be considered the most basic observations (Madsen 1995, 2003b). Other issues with the implementation arose due to limitations brought about by the relational Microsoft Access database engine. Numerous workarounds and hard-coded exceptions had to be made to accommodate the desired user interface and functionality. Eventually the number of tables and relationships grew into an extremely complicated structure (see fig. 6.10), while the limitations to the user interface provided by Microsoft Access Forms, rather than the actual data model, became a constraint. At the same time, the risks of developing a database using proprietary platforms, which are under continuous development, have become abundantly clear as it is today impossible to run ArchaeoInfo databases on modern operating systems, using recent versions of Microsoft Office. It demonstrates how important interoperability of conceptual data models is, and why data should always be organised in an intuitive, simple and ordered way, which allow for efficient queries and human-readable access; even if the front-end breaks.

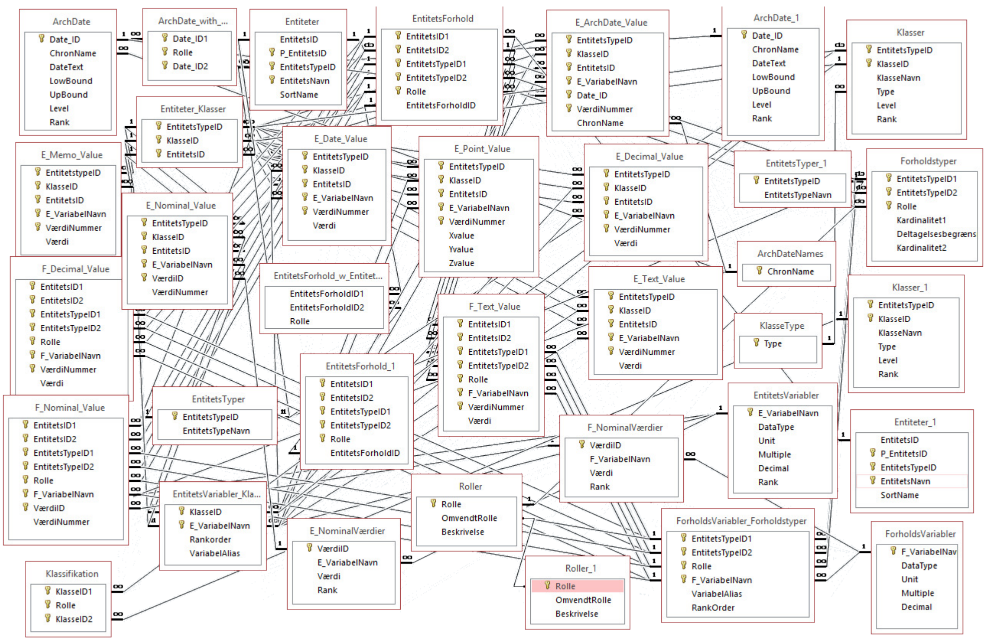


Figure 6.10: The relatively complex relationship diagram of the ArchaeoInfo database, when the data model is realised using Microsoft Access RDBMS (Madsen 2003).

The apparent simplicity and transparency of the conceptual model is noticeable and valuable (see fig. 6.9), not least compared to otherwise very common chaotic entity-relationship models, but it conceals a relatively complex implementation model due to its extensive use of many-to-many relationships and link tables. The reason why the IDEA and ArchaeoInfo databases still stand out, is due to their relatively early and successful attempt at combating the inherent complexity of relational models by applying object-oriented modelling principles to archaeology (Dallas 1992, Booch 1999).

6.4.2 Object-Oriented models, EAV and NoSQL

The object classification system, implemented by the IDEA and ArchaeoInfo databases for describing the contents of the individual Constructs, Layers and Objects, was prototyped and developed into an extremely simple yet powerful and flexible solution for dynamic classification and description (Andresen and Madsen 1996b). By employing three tables; Object – Variable – Value as linked one-to-many relationships, it became possible to have an unspecified number of variables and values associated to each object (see fig. 6.11).

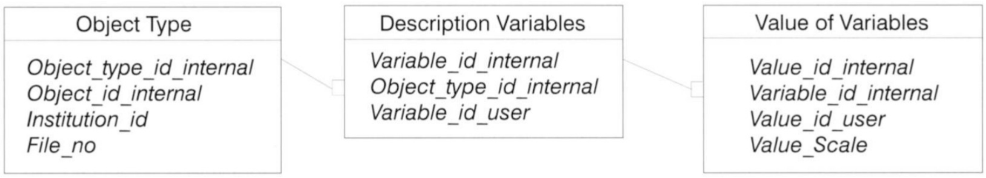


Figure 6.11: IDEA EAV-model (Andresen and Madsen 1996a).

These object-oriented considerations were in fact the precursor to what is today a well-known technique for utilising a relational database management system as an object-oriented platform, known as Entity-Attribute-Value (EAV) ordering. Rather than having tabular representations of rows and columns, where each column would represent a specific attribute, data is stored in a space-efficient manner. The number of attributes (properties or parameters) which may be used to describe an entity is potentially vast, but the number that will actually apply to a given entity is relatively modest, as it only exists once assigned.

Table 6.4: Traditional tabular data structure.

Entity	Type	Material	Width	Height	Diameter	Prod. year	...
#1	Coin	Silver		0.4 cm	2.5 cm	A.D. 250	
#2	Axe	Flint	10 cm	3 cm			
#3	Sample	Soil					
...							

In the EAV-model, the entity is the object or class, which is being described: the attribute is the property or variable, which describes it; while the value can be any of a series of textual, continuous or classification data (text or number

- or in certain cases - binary or geometry data, which we shall return to). The EAV-model partially mimics the behaviour of a graph database which uses graph structures for semantic queries. Basically nodes, edges and properties represent and store data and an edge (graph) directly relates data items. The relationships allow data in the store to be linked together directly, and in many cases retrieved with one operation.

Table 6.5: Entity-Attribute-Value (EAV) data structure.

Entity	Attribute	Value
#1	Type	Coin
#1	Material	Silver
#1	Height	0.4 cm
#1	Diameter	2.5 cm
#1	Prod. year	A.D. 250
#2	Type	Axe
#2	Material	Flint
#2	Width	10 cm
...	...	...

The dynamic and flexible nature of the EAV is why it is such a powerful way of organising archaeological data. Arguably, archaeological data are NoSQL – meaning they are not always structured in a tabular way like relational databases. For instance a series of finds may share some properties, but they are not necessarily universal among all finds. A find of type “coin” may have the property “year of coinage”, which make no sense for a find of type “ceramics”. The relational model would require separate tables for different types of finds, or leave many blank fields for each property which is unassigned.

Another advantageous characteristic of the EAV-model is the way it allows for explicit modelling of absence. In common tabular data representations, an empty cell or a missing value is rarely described explicitly: does it mean that data was not recorded or that the value is “nothing”? Or simply that this particular attribute does not apply for the given entity (see table 6.4)? In the EAV-model, the absence or presence of an attribute corresponds to knowledge rather than uncertainty, and directly represents a “true” or “false” statement. Accordingly, attributes may simply be used as boolean values or “tags” which describe an entity without the need of an added value. The mere presence of the attributes “bone”, “human”, “femur” is enough to build a strong classification system (see table 6.5)

In the object-oriented model, the object is the central concept, rather than the relations. It arises out of a desire to treat not just the static data-oriented aspect of information, as with the relational model, but also the dynamic behaviour of a system – and it is therefore far more flexible. As with the entity-relational model, the static concept of an object is expressed by a collection of named attributes. However, it exhibits a dynamic behaviour. Each object is characterised by a predefined set of attributes, which are then instantiated as separate instances, classes or entities, and inherited. For instance, a "find" object may be instantiated differently depending on whether it is a coin or a piece of ceramics, and it may be described through different sets of attributes, but retain its relation to the overarching conceptual notion of a "find".

There are dedicated NoSQL database management systems on the market, of which MongoDB is probably the best-known. Of the most important benefits, scalability and increased performance compared to relational models are often mentioned, while the simpler storage of, for instance, key-value pairs or as actual graph stores is a much more object-oriented approach. This leads to where archaeological data management currently appears to be headed: towards data, which is not relationally structured, but employs the Resource Description Framework (RDF) in triplestores as subject-predicate-object triples (Candan et al. 2001; May et al. 2011, 2012; Wright 2011). This is not unlike the philosophy of the EAV-model. However, when working with large datasets and complex queries, the standard SQL queries of a relational DBMS become unreasonably complex and slow, and require nested sub-queries to complete even relatively simple queries. The SPARQL query syntax allows for far more efficient queries into RDF triplestores (Shaw 2010).

6.5 Conceptual reference models and ontologies

The development and implementation of the CIDOC Conceptual Reference Model (CIDOC-CRM) is by far the most important emerging contribution to modern archaeological datasets. It provides an extensible ontology, covering concepts in cultural heritage and museum documentation, which allows for the benefits of semantic interoperability of archaeological data across different domains, cultural and national borders. The CIDOC-CRM acts as an overarching conceptual data structure schema, which is not only endorsed by the International Council of Museums (ICOM), but also ties into the work of the Open Knowledge Foundation and is increasingly applied across the broader heritage section and GLAM institutions (Galleries, Libraries, Archives, Museums) for data exchange. The formal semantics, which the CRM represents, is a direct precondition for data becoming machine-readable, and is the foundation for Semantic Web infrastructures. ARIADNE is a European Commission funded digital infrastructure focussed on the archaeological and heritage sector, based around the CIDOC ontology to make distributed datasets available across periods, domains and regions in a far more coherent and homogeneous way. Data is aggregated from fragmented datasets across Europe (including institutions and projects as ADS, SNDS, DANS, DAI and Fasti), mapped to CIDOC-CRM and made findable and accessible online through the ARIADNE Portal (`http://portal.ariadne-infrastructure.eu`).

While the first development of CIDOC-CRM in the early 1990s by the CIDOC Documentation Standards Working Group was focused on the development of an entity-relationship model, this approach was eventually abandoned for an object-oriented modelling strategy, resulting in the first CIDOC-CRM specification in 1999. Interestingly, this process reflects the development of archaeological data models from relational to object-oriented, as presented above. Through the early 2000s CIDOC-CRM matured, as work of standardization progressed, until becoming an ISO standard by 2006.

> "The CIDOC Conceptual Reference Model (CRM) provides definitions and a formal structure for describing the implicit and explicit concepts and relationships used in cultural heritage documentation...to promote a shared understanding of cultural heritage information by providing a common and extensible semantic framework that any cultural heritage information can be mapped to. It is intended to be a common language for domain experts and implementers to formulate requirements for information systems and to serve as a guide for good practice of conceptual modelling. In this way, it can provide the "semantic glue" needed to mediate between different sources of cultural heritage information, such as that published by museums, libraries and archives."(Doerr et al. 2011)

The CIDOC-CRM includes a top-level ontology, which describes a set of general terms (entities, properties and relations), while the domain ontology provides definitions to the related concepts; classes, attributes and relationships. For instance the CIDOC-CRM core classes cover concepts of material things (physical persistent items), immaterial things (symbolic or conceptual), events and space-time.

The current specifications (6.2.2 by September 2017) include 99 core classes or entities (E1-E102), while it defines 177 properties (P1-193) (see excerpt in table 6.6).

While the core classes and properties, at least from an information science point of view, aim to conceptualise every thing and every event in the real world, it does not cover all the intricacies of very domain-specific concepts. The CIDOC-CRM is, however, extremely extendable (see table 6.7) which is one of the biggest strengths; but perhaps arguably also one of its weaknesses.

In realising that the core CIDOC-CRM entities do not cover all archaeology-specific concepts, the STAR (Semantic Technologies for Archaeology Resources) project collaborated with English Heritage in developing an archaeological ontology extension for CIDOC (CRM_{EH}) (Binding et al. 2008; Cripps and May 2010;

Table 6.6: Excerpt of CIDOC-CRM classes and properties (Doerr et al. 2011).

Property id	Property Name	Entity - Domain	Entity - Range
P1	is identified by (identifies)	E1 CRM Entity	E41 Appellation
P2	has type (is type of)	E1 CRM Entity	E55 Type
P3	has note	E1 CRM Entity	E62 String
P4	has time-span (is time-span of)	E2 Temporal Entity	E52 Time-Span
P7	took place at (witnessed)	E4 Period	E53 Place
P10	falls within (contains)	E4 Period	E4 Period
P12	occurred in the presence of (was present at)	E5 Event	E77 Persistent Item
P11	- had participant (participated in)	E5 Event	E39 Actor
P14	- - carried out by (performed)	E7 Activity	E39 Actor
P16	- used specific object (was used for)	E7 Activity	E70 Thing
P31	- has modified (was modified by)	E11 Modification	E24 Physical Man-Made Thing
P108	- - has produced (was produced by)	E12 Production	E24 Physical Man-Made Thing
P92	- brought into existence (was brought into existence by)	E63 Beginning of Existence	E77 Persistent Item
P108	- - has produced (was produced by)	E12 Production	E24 Physical Man-Made Thing
P94	- - has created (was created by)	E65 Creation	E28 Conceptual Object
P93	- took out of existence (was taken out of existence by)	E64 End of Existence	E77 Persistent Item
P15	was influenced by (influenced)	E7 Activity	E1 CRM Entity
P16	- used specific object (was used for)	E7 Activity	E70 Thing
P20	had specific purpose (was purpose of)	E7 Activity	E5 Event
P43	has dimension (is dimension of)	E70 Thing	E54 Dimension
P46	is composed of (forms part of)	E18 Physical Thing	E18 Physical Thing
P59	has section (is located on or within)	E18 Physical Thing	E53 Place
P67	refers to (is referred to by)	E89 Propositional Object	E1 CRM Entity
P75	possesses (is possessed by)	E39 Actor	E30 Right
P81	ongoing throughout	E52 Time-Span	E61 Time Primitive
P82	at some time within	E52 Time-Span	E61 Time Primitive
P89	falls within (contains)	E53 Place	E53 Place
P104	is subject to (applies to)	E72 Legal Object	E30 Right
P106	is composed of (forms part of)	E90 Symbolic Object	E90 Symbolic Object
P107	has current or former member (is current or former member of)	E74 Group	E39 Actor
P127	has broader term (has narrower term)	E55 Type	E55 Type
P128	carries (is carried by)	E24 Physical Man-Made Thing	E90 Symbolic Object
P130	shows features of (features are also found on)	E70 Thing	E70 Thing
P140	assigned attribute to (was attributed by)	E13 Attribute Assignment	E1 CRM Entity
P141	assigned (was assigned by)	E13 Attribute Assignment	E1 CRM Entity
P148	has component (is component of)	E89 Propositional Object	E89 Propositional Object

May et al. 2011). An extension to the core CIDOC-CRM is needed to model "the core of the archaeological process, by which archaeologists attempt to record and document the results of past events through a series of events or activities in the present." (Cripps et al. 2004). An archaeological concept such as 'context' is central to context-based recording, but the specific nature or definition of what is actually referred to as context, differs immensely. It can be a cut of a ditch, a section of a wall, a skeleton, the secondary fill of a posthole or even a collected sample for analysis. It may be a place (deposits and structures) or an extend (cuts and features). The consensus in the case of CRM_{EH} was to think of context in terms of the CIDOC core class "E53 Place", which simply comprises: "extends in space, in particular on the surface of the earth... independent from temporal phenomena and matter". Clearly this is not a perfect match for the concept of an archaeological context, and the CRM was thus extended by the CRM_{EH} which comprises 126 extension sub-classes and 4 extension sub-properties to cover the domain. This includes "EH-E0007" to specifically describe archaeological context (see fig. 6.13).

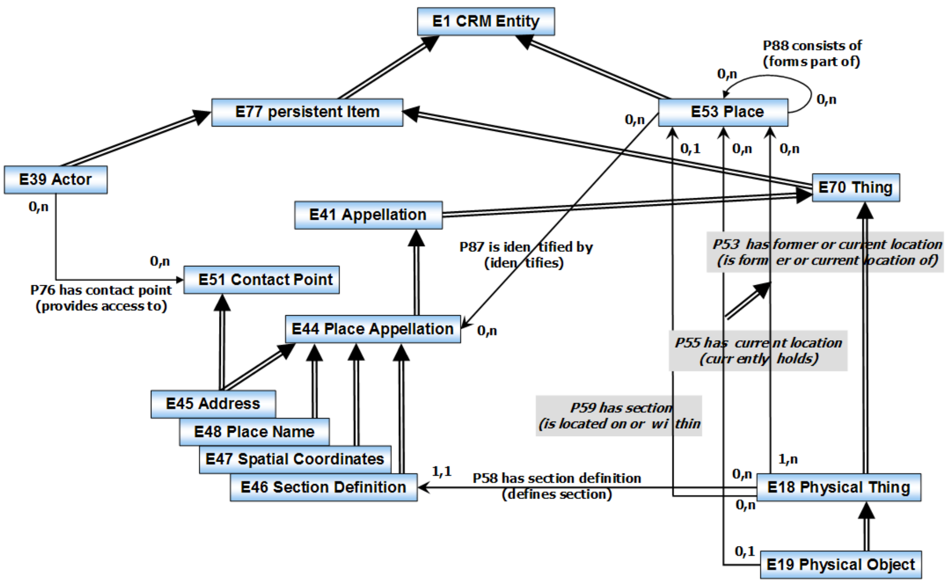


Figure 6.12: Reasoning about spatial information (Doerr et al. 2011).

In their 2004 paper, (Cripps et al. 2004) state: "In terms of content, the model is remarkably simple", however by any reasonable definition, the complete CRM_{EH} ontological mapping as shown in figure 6.13 is far from simple; but neither is it a simple reality, which it serves to model. CIDOC-CRM is an extremely strong conceptual reference model, and a solid framework for the exchange of data, particularly across domains, traditions and national borders.

It is, however, debatable how suitable a very complex conceptual model is for the actual excavation recording, when it is so strongly tied to the mappings of overarching ontologies and semantics. No matter how accurately the excavation process is modelled, covering the epistemological processes and very domain-specific archaeological concepts, it may appear discouraging to the average field archaeologist, seeking to make sense of the physical evidence, to find an additional daunting task of describing the archaeological process through a complex conceptual model. If, indeed, transparency of data and the process of knowledge creation is a priority, a complex CRM data model will arguably provide something which is far more complicated and less human-readable than was intended. It is also conceivable that archaeologists tend to think and work more in line with a relational or direct-hierarchical model. The tabular and relational model is a very familiar approach to archaeological datasets, and it is how hierarchies and attributes between archaeological concepts are commonly managed. An object-oriented data model like the CIDOC-CRM, which is operating at an elevated conceptual level,

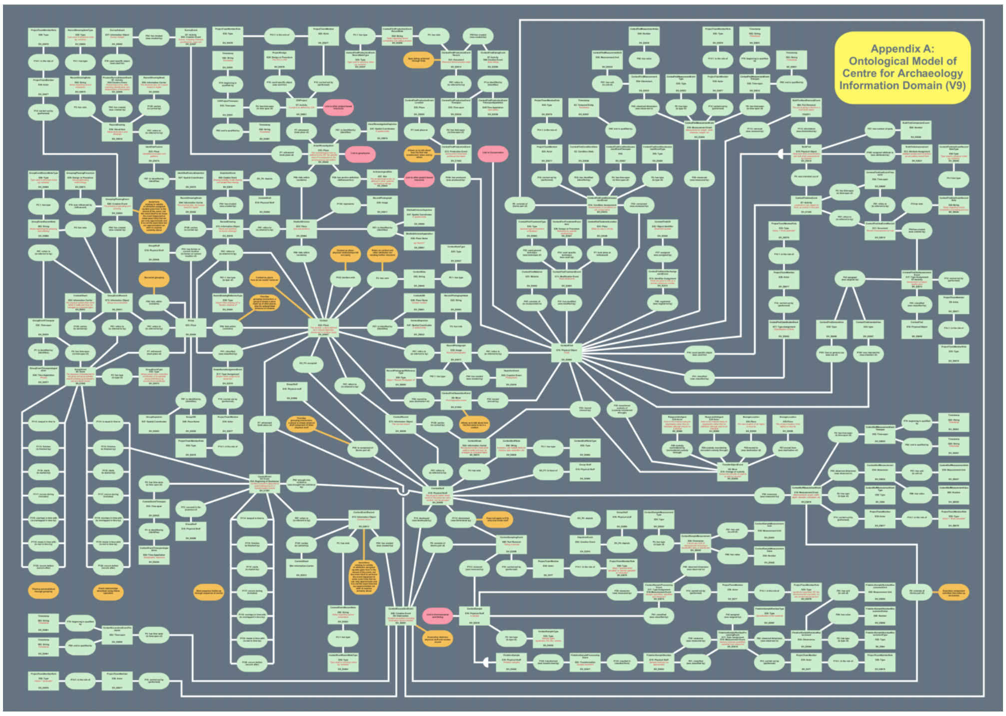


Figure 6.13: The CRM_{EH} ontological model (Cripps et al. 2004).

is perhaps perceived as very abstract and ambiguous, and most certainly requires an investment to truly comprehend.

This begs the question of where ontologies such as CIDOC-CRM leaves the public and the average data consumer. Data are made available through layers of abstractions on top of abstractions, and are not in any way self-describing, but dependent on iterations and emergence of extensions and revisions. And it is worth considering if for archival purposes, human readable text, perhaps json with relatively simple key-valued pairs, is the safest option, if we want to ensure that people and machines are able to make sense of data in 20 years time or more.

What the ontological model does provide, however, is an unprecedented detail of process and shared meaning within and beyond the archaeological sector, in particular regarding implicit vs. explicit knowledge embedded in a dataset. As a basic example, a very common piece of information in most tabular datasets is a date field. But very often it is implicit knowledge whether the date relates to a date in the (archaeological) past, the acquisition event (excavation) or the data entry itself, and any actor or events are not necessarily or explicitly accounted for. This is contrasted by a very explicit modelling of the CIDOC-CRM, which accounts for the creation process of "things" and "information about things" separately through

Table 6.7: CIDOC-CRM compatible extension models and collaborations status 01-2018. Sources: Binding et al. 2008; May et al. 2012; CRM-SIG 2018; Hiebel et al. 2017.

Extension	Target domain	Status (01.2018)
$CRM_{ARCHAEO}$	Model for archaeological excavation	Proposed for approval by CIDOC CRM-SIG
CRM_{BA}	Model for archaeological buildings	Proposed for approval by CIDOC CRM-SIG
CRM_{DIG}	Model for provenance data	Proposed for approval by CIDOC CRM-SIG
CRM_{EH}	English Heritage Centre for Archaeology ontological model	N/A
CRM_{GEO}	Model for spatio-temporal data	Proposed for approval by CIDOC CRM-SIG
CRM_{INF}	Model for argumentation and inference	Approved by CIDOC CRM-SIG
CRM_{SCI}	Model for scientific observations	Proposed for approval by CIDOC CRM-SIG
CRM_{TEX}	Model for the study of ancient texts and documents	N/A
$FRBR_{OO}$	Functional Requirements for Bibliographic Records	Work in progress
$PRESS_{OO}$	Model for bibliographic information	Approved by CIDOC CRM-SIG

Events and Activities such as “Beginning of Existence” and “End of Existence” (see fig. 6.14).

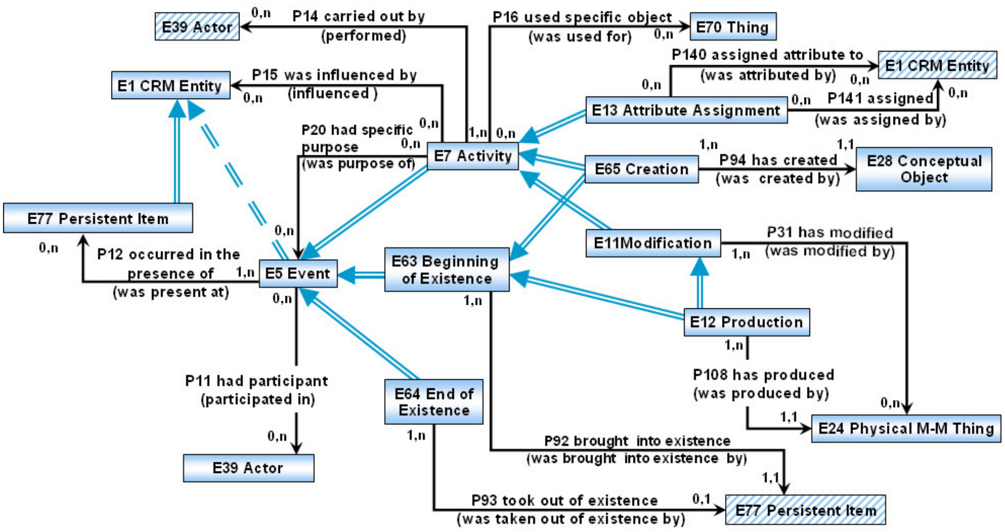


Figure 6.14: CIDOC-CRM Core Events (Doerr et al. 2011).

Considering that the CIDOC-CRM has existed since 1999 and undergone countless revisions before reaching version 6.2.3 (January 2018) with version 5.0.4 being the current official version, the momentum and active development of the framework is evident. From the point of view of this research project, it is however remarkable to witness, that the CRM_{GEO} extension, which includes the OGC concepts and spatial geometries to describe archaeological features, finds etc. has still not met approval and official implementation. And it is in direct conflict with the premise that spatial data is at the core of archaeological documentation. This will hopefully change soon, but inevitably raises the question why such a fundamental concept should not be part of the core conceptual model. Simultaneously, the $\mathrm{CRM}_{\mathrm{EH}}$ appears to be merging into the $\mathrm{CRM}_{\mathrm{ARCHAEO}}$ in order to formalise standards beyond that of English Heritage, yet detailed information about the progress of this and other planned extensions are difficult to find (see table 6.7).

6.5.1 Terminologies, thesauri and vocabularies

Beyond the ontological modelling lie the semantics of concept classifications – basically what we call things. An often overlooked characteristic of the physical entities we deal with in archaeology is how they take on different properties, depending on the point of focus and applied vocabulary. The precise nature of an entity is something which is often implied and not expressed explicitly. This is perhaps best demonstrated through the common use of the class type "Find" in Danish archaeological datasets. The exact nature is not expressed explicitly, but it is implied that it is some physical entity we "bring home from the excavation". In fact, it ranges from man-made objects and artefacts to soil samples, and it takes a lot of effort to align such data with an overarching conceptual framework. And even then, there is no guarantee that there is consensus among peers as to the definition of terms. Artefacts, for instance, are commonly characterised by inferring their use or function. This is something which is easily classified using an immediate vocabulary. Overarching classifications such as "coin", "flint axe", "ceramics" are terms which are commonly recognized and conceptually broad enough to classify and organise finds from an excavation. There are, however, intrinsic problems with this approach, which become immediately apparent. What is the function of the flint axe? Is it a tool or a weapon or a grave-good or something completely else? As discussed above, not all entities share similar attributes for classification. This may be solved through a dynamic EAV-classification scheme in an object-relational structure. Another problem relates to classification and typology hierarchies and is a well-known and common challenge to archaeological classification and how we handle nested and hierarchical structures (Dallas 1992, Andresen and Madsen 1996b). This is where conceptual frameworks gain versatility and extensibility from the Semantic Web using established vocabularies, thesauri, classification schemes, subject heading systems and taxonomies attributed to individual domains. For instance, an animal bone is a subclass of the more general term bone, and an artefact may be placed anywhere along a typology tree, ranging from the most general classification to the specific type or subtype (see fig. 6.15).

Differing levels of confidence are especially pronounced in archaeology, and further complicated by dynamic typologies where new types and orders emerge as new finds are introduced. From a data management viewpoint, a data model must facilitate that classification hierarchies are inherited. For instance should searching for a “flint axe” in a database also return flint axes of a specific type, which are a typological subclass of flint axe. The same applies to time periods: a search for finds from the broad term “Neolithic” should also return finds from the narrower term ”Middle Neolithic Funnel Beaker culture period IA”, but not necessarily the other way around. These semantic relationships within vocabularies are commonly divided into three categories of relationships; equivalence, hierarchical and associative relationships. In the equivalence relationship terms are indicated by ”Broader Term” and ”Narrower Term” designations in the thesaurus. The hierarchical relationship is a distinguishing feature of the thesaurus in contrast to a simple list of alphabetically ordered terms. This is usually represented using the Simple Knowledge Organization System (SKOS 2018) and provides links to superordinate “Broader Terms” which represent more general concepts than subordinate “Narrower Terms”. Equivalence relationships are made when two or more terms represent the same or nearly the same concept, e.g. synonymous, while an associative relationship is reciprocal and describes terms that are conceptually related but are neither hierarchical or equivalent.

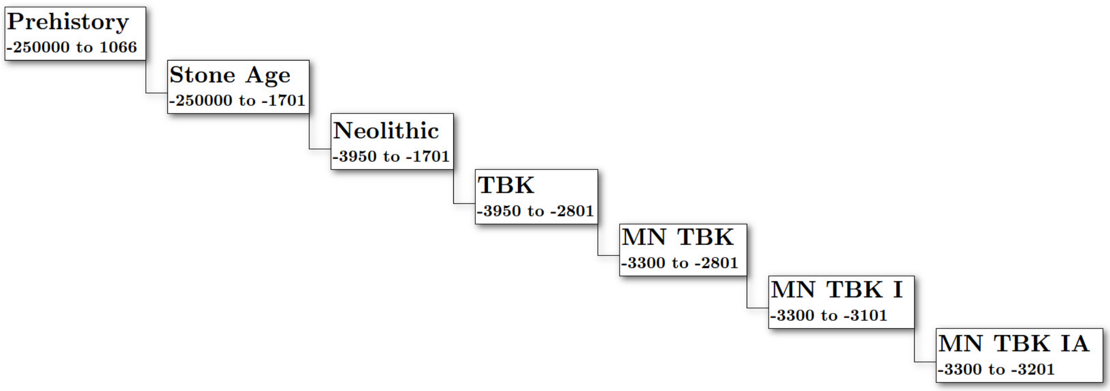


Figure 6.15: An example of a classification hierarchy. For both typological and chronological structures, a data model must be able to traverse hierarchical organisation, for instance, to ”know” that the Neolithic ”belongs to” prehistory, and that ”MN TBK 1A” is a sub-sub-structure of ”TBK” (Funnel Beaker culture).

Within archaeology, several online vocabularies or thesauri exist and are adopted as Linked Data Vocabularies. Historic England, Historic Environment Scotland (including the former RCHMS) and the Royal Commission on Ancient & Historical Monuments of Wales each provide extensive vocabularies for domain-specific archaeological concepts for instance archaeological objects, evidence, recovery methods and materials (FISH - Forum on Information Standards in Heritage 2018). Together with CIDOC-CRM these vocabularies become extremely powerful and may be used to describe endless properties of archaeological recording. For instance is the Art & Architecture Thesaurus Online (The Getty Institute 2017) used as the core mapping spine for subject terms in ARIADNE, while PeriodO offers mappings of archaeological periods (cultures) across geographic areas. This addresses the problem of “Bronze Age” or “Medieval” being distinctly different concepts when comparing, for instance, Southern Europe and Scandinavia.

6.5.2 Future directions

Some interesting observations can be made by example of Britain. The the development and discussion of ontological models in British archaeology was pronounced in the late 2000s, spawning several projects (Cripps et al. 2004; Binding et al. 2008; May et al. 2011, 2012; Wright 2011) and including efforts to combine the ontological model of archaeological practice with geospatial awareness (Cripps 2012, 2013). More recently, however, attention appears to have branched into two directions:

One branch, which is currently gaining traction in England is Historic Building Information Modelling (BIM). BIM has been in use by the architectural, engineering and construction industry for decades and is based on object-based parametric modelling applications. BIM is not simply a 3D CAD or a 3D visualisation tool; it offers greatly enhanced data management capabilities, effectively integrating geometry (2D and 3D), non-geometric information and linked documents and data. As a tool for managing excavation documentation it is promising, for instance, for handling phases and 4D (temporal) modelling of archaeological buildings and structures. It also allows for the integration of heterogeneous datasets, such as historic information, legacy data, photographs and drawings as well as geospatial datasets, geophysics and remotely sensed data. Furthermore it allows for integration of intangible information, such as significance and heritage values, etc. (Historic England 2017) and it will be interesting to observe in the upcoming years how such a versatile tool may affect archaeological practice. At the moment, Historic BIM shows little attention to analytical capabilities for spatial data, which still requires external processing in GIS, CAD or similar. More worrying is the lack of integration with ontologies, and hopefully we will see actions towards resolving this in the future.

The other branch hints at a departure from the focus of May et al. on modelling the archaeological fieldwork process to look more at the overarching interoperability of archaeological datasets; for instance through developments within ARIADNE. Simultaneously, IntraSIS (IntraSIS 2016) has been endorsed by Historic England, with incumbent implications for excavation recording. Even though the IntraSIS data structure is customisable, it is to at large extent proprietary and dependent on proprietary software (ArcGIS) for its functionalities. Indeed, it has not been possible during this project to get immediate access to documentation of the IntraSIS data model. One thing is however certain: IntraSIS is not the ideal choice in the pursuit of the FAIR principles being promoted by ARIADNE amongst others (Wilkinson et al. 2016; Aloia et al. 2017). The basic premise of IntraSIS is not unlike that of the IDEA database, which is either a stand-alone or local server-client setup, and it was not developed to take advantage of the strengths of the Semantic Web, online vocabularies or ontologies for interoperability. The imperative question is where this leaves archaeological data, if just intended as a reporting tool for rescue excavations, and does not encourage data re-use.

Arguably, if archaeological documentation is meant for CIDOC-CRM somewhere down the pipeline, why not implement the CIDOC and/or $\mathrm{CRM}_{\mathrm{ARCHAEO}}$ at the data entry level; eliminating the excessively time consuming efforts of mapping and translating data from one data model to another? And what is the risk to archaeological data, stored in proprietary systems?

One system deserves mentioning, as it is one of the most flexible and well-documented systems currently available, as well as being open source and under continuous development: the ARK Toolkit framework developed by L P: Archaeology (Eve and Hunt 2008, Eve et al. 2018). At its core, the ARK data model is almost identical to the IDEA model of Madsen and Andresen (1996a) and from that standpoint alone, it is interesting that two systems developed 20 years apart share the same ideals. They are both based around the object-relational paradigm, and use Entity-Attribute-Value triples to store everything. This effectively means that "all data is data" and handled seamlessly regardless of type, domain or origin. Furthermore, ARK is modular and highly customisable, as demonstrated by the variety of projects using ARK, such as FASTI Online (AIAC 2004) and the Digital Metal Detector Finds (DIME). Another interesting observation is that the ARK framework is based upon a relational DBMS also similar to IDEA. This is obviously related to how ARK is meant to be distributed and installed on local servers for individual projects, and a good argument for not pursuing object-based or NoSQL solutions for field archaeological data storage.

In that respect the ARK philosophy is in line with current trends of NOT trying to force all current and future databases into one common system. Instead it allows for the individual database, tailored to fit a specific research purpose. On top of that, ARK provides mapping to CIDOC-CRM or other ontologies, and ensures links to vocabularies and the Semantic Web.

What remains is how a complex conceptual model like CIDOC-CRM is perceived and accepted by the broader archaeological community. Inevitably something happens to archaeological data once it reaches a state where only information- and computer scientists can make sense of it, and we should not abandon relational and object-oriented databases just yet. In catering for field archaeologists' data this obligation should not be forgotten. If archaeologists who are meant to be interpreting and synthesizing archaeological data expect simple, tabular data, this should not be a complex manoeuvre to produce – no matter how data is managed.

6.6 The Archaeo Framework

From the outset of this research project, the implementation of data models in archaeological practice has been a key consideration. The research questions have all been approached through a bottom-up approach, as reflected in the case studies presented in the individual chapters. At the core lies a well-defined need for efficient ways to manage spatial integration, specifically by the excavation data produced and developed from research excavations such as Skelhøj, Jelling and Alken Enge. The method development presented should be considered an exemplification and does not aspire to be a universal method. This way, the goal of this research becomes a conceptual apparatus itself, and implementation has therefore been the principal driving force and strongly influenced how the project has progressed, while priorities inevitably have shifted along the course of the three-year study. One priority in particular which has changed, is the integration of distributed data other than spatial data. As the possibilities of integrating other data sources, such as the museum excavation data (MUD) developed, the value of harnessing and aggregating all excavation-relevant information through the use of web services became a priority. That means building a data-silo which dynamically collects data from different sources. While it has been important to prioritise data models and the theoretical and conceptual frameworks, the strong attention to implementation means that the technical preconditions, i.e. database management systems and front-end design, have influenced the data modelling process as well. It was also realised that the most pressing requirement to achieve data integration was the development of an intermediate data model to go between the conceptual structures of excavation methodology and the archival features of CIDOC-CRM enabled frameworks like ARIADNE. The challenge lies in the development of a model, structure and framework which accommodates these transactions: how do we tie another conceptual model to an existing data structure, and what kind of meta data is required? And how do we map or align different concepts and data types of one system to fit within the framework of another? The Archaeo Framework was constructed to act as a testing-ground for various implementation approaches to these issues.

6.6.1 Data model implementation

Prior to this research, some preliminary experimentation was associated with the development of the event-based documentation principles, and included under an umbrella of the ERAS (Event-based Recording and Archiving System) (Jensen 2012) developed through research excavations of Aarhus University. First versions were based around ESRI geodatabases, dedicated .NET Windows desktop frontends with online Microsoft Access/XML back-end, while an online PHP/MySQL platform was specifically developed for field recording and data entry at the Alken Enge excavations. The ambition to further integrate complex spatial data produced at excavations (i.e. image-based 3D recording) meant that the first considerations for implementation framework were inclined towards a cross-platform desktop application, with an online spatial-enabled database back-end. At the time, this was considered feasible by combining a PostgreSQL database with PostGIS extensions and a cross-platform user-interface developed in Python, using QT-libraries for the OpenGL graphics handling, compiled for Windows, Linux and MacOS. Furthermore, PostGIS support geometry data types for en spatial data stored in the databases, which allowed for spatial queries and efficient storage. An important advantage of PostgreSQL and PostGIS over other database management systems was their support for 3D geometry, which is still not commonly available anywhere else.

During the course of the research, the potential of HTML5 and JavaScript support libraries for the visual components, and the justification for developing a GUI or desktop application which the user had to install, became obsolete. Further inspiration came through collaborations with Galeazzi (Galeazzi 2016; Galeazzi et al. 2016) who at the time was working on the development of the ADS 3D Viewer (Galeazzi 2014) at the University of York. However, the ADS 3D Viewer did not support segmentation of 3D data, as I deemed a necessity in order to succeed in spatial data integration. Instead I decided to modify the open source three.js libraries to integrate an online 3D viewer, which in combination with the Leaflet.js 2D map libraries make up the spatial front-end of the framework. Another way the collaboration with the Archaeology Data Service (ADS) has manifested itself in this research is through the inspiration gained from insights into the ADS archival procedures. Learning how the ADS CMS system handles incoming excavation data, and how data is transformed into separate archival and dissemination versions was inspirational. In particular the efforts made to track changes to files going from submitted data through to archival data, and the document to progress leading to storing data using open data standards and file formats. The use of checksums to identify files and the exact version of a file is something I chose to employ in the Archaeo framework, and is an essential feature of the ArchaeoScraper module, which associate all incoming data to a specific source file (see chapter 4.6).

Finally there were some general technical design considerations related to how we store and manage spatial data. Vector data, such as points, lines and polygons are easily stored in many present-day database management systems as a geometry data type. In a relational database like PostgreSQL or MySQL this means that it is possible to perform spatial queries such as “select all geometry within a bounding box defined by these coordinates”. Yet the spatial extensions are not identical;

PostgreSQL 10.0 with PostGIS 2.4 extension has support for 3-dimensional geometry, such as 3D points and 3D lines, while the native geometry in MySQL 5.7 only supports two-dimensional geometry. MySQL is clearly targeting two-dimensional mapping services, using the OpenGIS Geometry Model, for which it is quite efficient. Bringing the Archaeo framework from the intended Python/PostgreSQL environment to the browser-based HTML5 equivalent and using PHP as scripting language, meant gauging pros and cons between the two database management systems. From a web hosting point of view, even locating a commercial solution which offers PostgreSQL and PostGIS as part of a standard solution is quite difficult. By comparison almost any web hosting company provides open source PHP and MySQL databases, often as part of even the most basic setups (W3Techs 2018).

6.6.2 Conceptualising spatial data

Each of the preceding chapters has revolved around one common theme: the lack of spatial integration in archaeological data models. It has been demonstrated how the application of digital techniques to different excavation traditions and methods affected how data is managed and perceived – as archaeologists try to negotiate state-of-the-art methods with traditions and compatibility with legacy data. While to some extent, we do already have spatial integration via the extensive use of GIS in archaeology, it never appears explicitly in prevailing data models. Modern archaeological methods have to some extent been shaped by the "behaviour" of desktop GIS and affected how the archaeological record is perceived, for example when the use of polygons requires well-defined boundaries in soil colour and texture, and does not respect the "fuzzy" reality archaeologists deal with. The use of GIS has also asserted the use of layers as proxies for observed strata, and has thus neglected to explicitly model the third dimension, as demonstrated by the lack of tools to handle vertical sections in the context of GIS. As discussed above, the inherent limitations of GIS are that they do not handle complex relations well, nor is GIS able to represent and integrate data without a geographic dimension in the same data model. This entails that data modelling is done outside of the limits of desktop GIS, and requires that spatial data is made explicit and conceptualised in such a way that it behaves as any other archaeological data.

To do so, the legitimate solution would be to manage spatial data just like any other piece of archaeological data: by assigning unique identifiers (Roskams 2001:112) . This is, of course, a tremendous undertaking if we were to manually assign sequential numbers to each graphical or geometric element in a spatial representation or drawing, as discussed in chapter 4.3.1. There is no other solution than letting the computer control this – it must, however, be visible and explicit, in order to successfully integrate spatial representation as a fully conceptualised entity. This has the direct advantage of moving beyond the immediate 1:1 relationship of geometry and attribute data provided by GIS, meaning that we instead can have multiple geometries representing each archaeological feature. Geometries become related to an entity through a one-to-many relationship, such that many different geometries (polygons, points, lines, segmented 3D meshes, voxel groups – each with unique identifiers) may represent a given entity. This is, for instance, required when multiple Documentation Events record the same posthole. Conceptually, the posthole is assigned a single unique identifier during the excavation, but any number of geometries with their own unique identifiers may represent the posthole. In the Archaeo Framework these geometries are all considered a separate class type (see tables 6.11 and 6.13). The relationship between geometry and archaeological entities are described explicitly as part of the stratigraphic matrix or event-based documentation, and does not require the conventional use of GIS layers to illustrate this. By organising all geometry in one "layer", and instead make use of the related attribute data, events and classes to visualise layers based on various search criteria, provides an extremely flexible approach. The immediate appearance is thus that all geometry lies on top of each other, seemingly devoid of structure. Structure is, however, derived from the data model, such that any geometry (spatial entity) in the data model exists explicitly, and is not confined to a specific predefined GIS layer or context, and may be visualised dynamically through queries (see chapter 6.7.1 and 6.7.2).

Arguably, handling vector data in the data model is fairly straight forward. However, due to the varying support of OGC standards, it was decided not to make use of the dedicated geometry data type. Doing so, eliminates any incompatibilities when migrating between, for instance, MySQL, PostgreSQL and even Microsoft Access DBMSs. The solution is much more in line with the philosophy of the data model; keep everything as simple and transparent as possible: all data is stored as text. Comparative tests revealed no significant difference in performance or transfer speeds between PostgreSQL or MySQL databases in identical software environments when using either geometry data types or plain character (long text) data types. It is a consideration of weighing the advantages from utilising a geometry data type as data storage, compared to pursuing an open data philosophy and storing everything as open text, and leaving it to the database abstraction layer to interpret or cast any data type from clear text to its proper type (text, number, boolean, geometry, etc.). In fact, SQL queries allow any text to be interpreted or cast as geometry during query, allowing spatial indexing and selection.

Vector data is inherently easy to store in any data model, as we may utilise the OGC WKT (Well-Know Text) or GeoJson protocols to encode any geometry as a text-string - even 3D geometry. In table 6.8 the implementation of spatial data in the database is illustrated. Each data type is associated with a predefined spatial classification variable in the *variables* table (see section 6.6.4).

Table 6.8: Example of how spatial data are stored in the Archaeo database (*classifications* table) using WKT and GeoJson protocols. Using variable 901: ”2D geometry, horizontal”.

Domain	Entity	Value
SBM1028	GC17	{”type”:”Polygon”,”coordinates”:[[[9.8521141002,56.046650839],[9.8520661104,56.046648587], ...
SBM1028	GC18	{”type”:”Polygon”,”coordinates”:[[[9.8521141582,56.046650860],[9.8521101149,56.046677657], ...
SBM1028	GC19	{”type”:”Polygon”,”coordinates”:[[[9.8521100774,56.046677697],[9.8520620877,56.046675447], ...
SBM1028	GC20	{”type”:”Polygon”,”coordinates”:[[[9.8521101149,56.046677657],[9.8521073343,56.046695646], ...
SBM1028	GC2648	{”type”:”MultiPolygon”,”coordinates”:[[[[9.8522982297,56.046712803],[9.8522982351,56.046712721], ...

For implementation and demonstration purposes, the Archaeo database is equipped with spatial classes for two- and three-dimensional spatial representations. These classes may be instantiated using one or more geometry attributes including: “2D geometry horizontal”, “2D geometry vertical”, “3D geometry” etc.

In contrast to vector data, there is currently little justification to integrate raster data or images into the data model as text. Firstly, it would result in losing the efficient transfer speeds and compression of raster file formats suitable for http-transfers (primarily jpg), and in addition, the use of rasters for anything but visualisation purposes (3D textures or background maps) is from the data model point of view extremely limited. It is however technically possible to integrate rasters as text in the database (RGB values in an array), should such a need arise.

6.6.3 Conceptualising temporal data: Two-level event-based recording

The Archaeo data model is event-based, meaning that no data or records are ever deleted. Rather, by employing “soft-deletes” where every entry is recorded by date and time and the responsible actor, everything remains as an uneditable entity in the database, but may be flagged as deleted at a certain time by a specific actor. The actor may either be a registered user (archaeologist) or any of the framework’s modules (i.e. ArchaeoScraper). This supports the para-data generation at the archival level.

At a higher conceptual level, the use of Data Collections and Documentation Events during and post excavation maintain para-data at the level of data generation associated with excavation recording. How we use Documentation Events as a conceptual abstraction of the data collected in the process of archaeological excavation is discussed in more detail in chapters 3.3 and 4.3, but generally speaking the Documentation Event accounts for the archaeological process and records the activities and events associated with excavation data. Thus metadata is generated which enables the evaluation of documentation quality and the management of multiple representations of the same entity. The Documentation Events also act as a tool for stratigraphic encoding, as each Documentation Event is usually defined as a three-dimensional spatial extent, and any measurements of elevation may be applied to any 2D geometry related to it. This allows for 2.5D representation as shown in chapter 6.7.1, where otherwise flat two-dimensional polygons are elevated in a 3-dimensional representation to visualise the stratigraphic sequence or vertical progress of the excavation.

6.6.4 Database structure and abstraction layer

To safeguard the dynamic nature and interoperability of the data model as described above, the basic principle of the Archaeo data model is an object-oriented approach in a relational entity-attribute-value (EAV) configuration. At its core sits only three database tables: *classes*, *classifications* and *relations*. Any entity-attribute relation may be described this way, and the structure is as useful for archaeology as it is for modelling any other physical properties of reality. As in almost any design process, exceptions and workarounds are necessary, even if contrary to the goal of a simple and transparent data model. For practical reasons an additional table, intervals, was included to manage temporal queries. Temporality is very specific by the way it is conceptualised in archaeology. Archaeological entities are commonly assigned to a relative chronology of arbitrary intervals, related to abstract archaeological constructs referred to as “cultures” or “periods”. These are essential to the archaeological nomenclature and ordering of things, and have been so since C. J. Thomsen’s three-age system in the early 19^{th} century. Three additional axillary tables manage the conceptual integrity of the database, with *variables*, *chronology* and *relationTypes* acting as intermediaries between the entities and the conceptual, ontological and semantic mappings (see fig. 6.16).

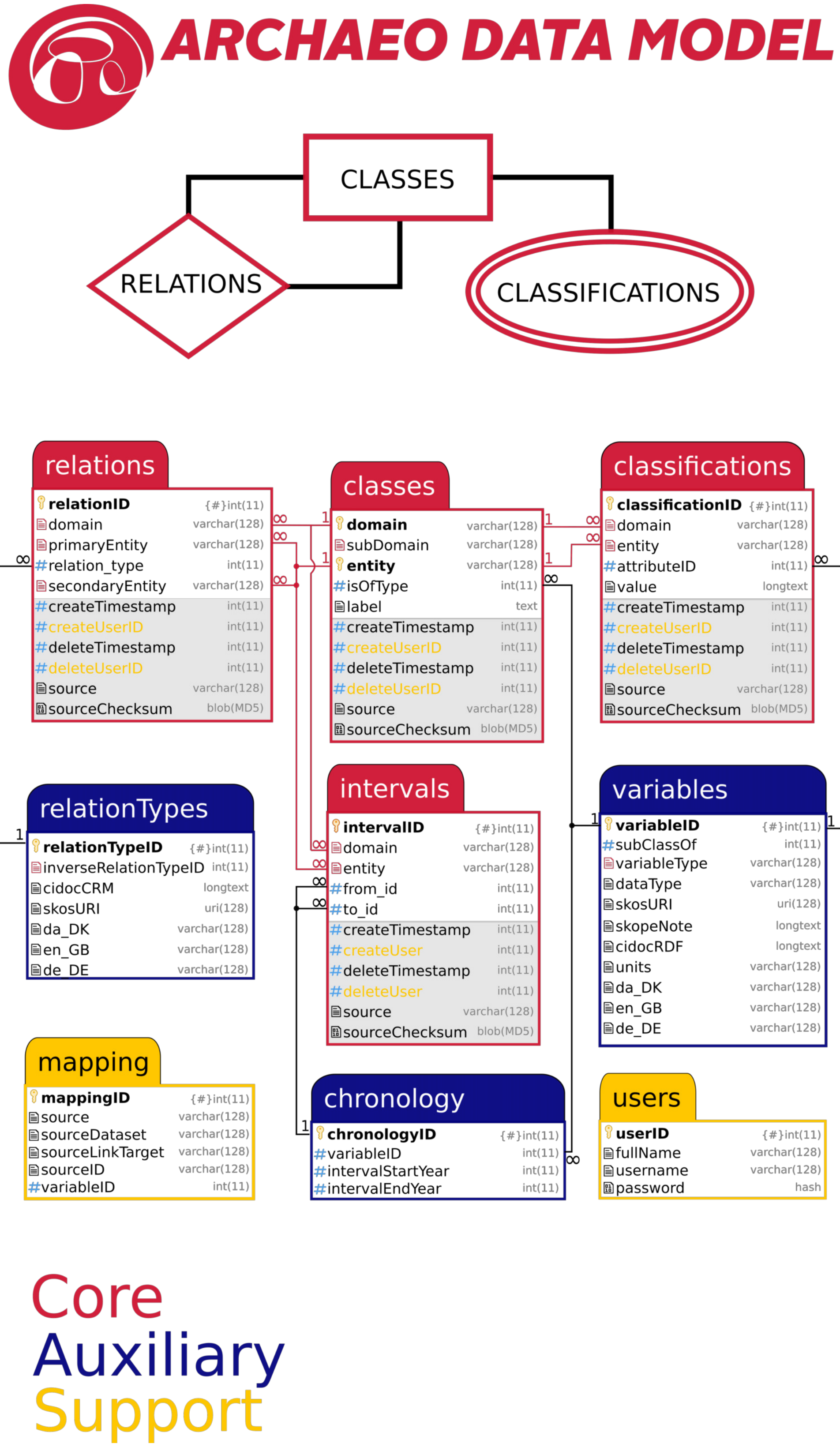


Figure 6.16: The Archaeo Framework E-R diagram and data structure.

Classes

The *classes* table contains instances of all entities in the database, and includes the associated basic attributes (*isOfType* and *classLabel*), which are included in support of efficient user interface integration more than it is a direct structural necessity. Additionally, every entity is defined by a *domain/subdomain* which is either a conceptual, inferential, hierarchical, or structural relationship, such as country, institution, site, campaign etc. Together, the *entity* and *domain* make up the composite primary key, which uniquely identifies, for instance, a find or feature within a specific archaeological site (*domain*), while the *subdomain* assigns the entity to a specific campaign or excavation event, belonging exclusively to the site in question. The different class types available include, but are not limited to:

- Archaeological conceptual entities:
  - Finds, features, (single-) contexts.
    All the things we usually manage in lists.
- Special conceptual entities:
  - Structures, meta-structures, Data Collections and Documentation Events.
    All of these classes behaves as super-classes for other classes and are used to organise the high-level site interpretation, produce illustrations and visualisation which combine several sub-classes and manages the administrative/ para-data documentation generation process.
- Excavation-technical entities:
  - Trenches, sampling grids, vertical sections, drawings, photos.
    All the physical surfaces, which are spatially defined and correspond directly to an excavation activity.
- Spatial entities:
  - GPS-points, vector geometry/delineation, georeferenced raster images, 3D point clouds, voxels and meshes.
    All spatial elements which derive from some digital sensing equipment, including scanning of legacy excavation plans.

Table 6.9: Excerpt and structure of the *classes* table in the Archaeo database. A series of finds (class: 3), from Alken Enge (domain: SBM1028).

Domain	Subdomain	Entity	isOfType	Label	CreateTimestamp	CreateUser
SBM1028	2012	X980	3	Human hand bone (distal phalange). Complete.	1346951675	5
SBM1028	2012	X981	3	Ceramic fragment. Found in gytje.	1346951878	5
SBM1028	2012	X982	3	Stone (big). Found in mixed sand and gytje.	1347195923	5
SBM1028	2012	X983	3	Fish bone. 2 pieces.	1347196133	5
SBM1028	2012	X984	3	Shield wood.	1347196193	5
SBM1028	2012	X985	3	Human patella.Found in mixed sand and gytje / dark sand.	1347196220	5
SBM1028	2012	X986	3	Human vertebra. Found in mixed sand and gytje / dark sand.	1347196253	5

Classifications

The *classifications* table contains all the values or attributes we may assign to the classes, and acts as the triplestore of the entity-attribute-value (EAV) model.

- Any attribute/value pair is stored as plain text. This includes boolean, text, integer, float, date and geometry data types, which are cast from plain text to their respective data type through the database abstraction layer.
- The attribute itself is handled by referential link to the *variables* table.

Table 6.10: Excerpt and structure of the *classifications* table in the Archaeo database. Attributes correspond to classifications defined in the *variables* table (see table 6.13). Values of *-1* are a boolean *true*-value.

Domain	Entity	Attribute	Value	CreateTimestamp	CreaterUser
SBM1028	X810	59	-1	1344869700	6
SBM1028	X810	160	-1	1347128953	5
SBM1028	X810	110	-1	1347128988	5
SBM1028	X810	61	23-07-12	1347128999	5
SBM1028	X810	73	23-07-12	1347129010	5
SBM1028	X810	108	-1	1347129040	5
SBM1028	X810	181	-1	1347129048	5
SBM1028	X810	155	Lene Mollerup & Pernille M. Boye Thulstrup	1347129212	5
SBM1028	X810	120	-1	1347129248	5
SBM1028	X810	168	-1	1352196791	5
SBM1028	X810	86	-1	1385637106	5
SBM1028	X810	65	Almost complete skull (the left zygomatic arch is missing).	1396627442	5
SBM1028	X810	130	Present. Palentine torus. Possible porotic hyperostorose.	1396627521	5

Relations

The *relations* table holds all the explicit relations between entities. These may either be recursive or hierarchical, and may be both physical and conceptual relations. The current data structure restricts relations to entities within the same *domain* (i.e. site). Domains, however, act at different levels, ranging from countries and sites to the individual artefact or 3D point.

- Triplestore of *primaryEntity* - *relationType* - *secondaryEntity*.
  - Any relationship between classes (physical or conceptual) may be represented through this many-to-many relationship, including recursive relations.
  - The relation type and inverse relation are handled by the *relationTypes* table.

Table 6.11: Excerpt and structure of the *relations* table in the Archaeo database. Relations correspond to relationships in the *relationTypes* table. In this example, the secondary entities with the prefix GC are Geometry Collections - a separate class which holds all spatial representations, and allows every entity to be assigned several visual representations.)

Domain	PrimaryEntity	Relation	SecondaryEntity	CreateTimestamp	CreateUser
SBM1028	X810	14	D1360B20120723A	1347128974	5
SBM1028	X810	11	D1360	1347128983	5
SBM1028	X810	6	I14	1369755503	5
SBM1028	X810	14	D1360B20120723B	1503601942	1
SBM1028	X810	21	GC5149	1506960059	1
SBM1028	X810	14	D1360B20120723B	1506960059	1
SBM1028	X810	21	GC5150	1506960059	1

Intervals

The function of the *intervals* table is to map between the entity and the temporal relative dating. It takes into account that the precision by which archaeological entities are dated is usually restricted to a *terminus post quem* or *ante quem*, meaning that the dating falls between two extremes. These extremes may not be defined by absolute calendar year, but by period or culture, which is why an extra layer of abstraction is needed and expressed explicitly through this table, which also facilitates efficient temporal queries.

- *From_id* and *to_id*
    - Relates to an extensible array of archaeological or cultural periods, handled by the *chronology* table.

Table 6.12: Excerpt and structure of the *intervals* table in the Archaeo database. Entities are linked to start- and end periods, which are defined in the *chronology* table.

Domain	Entity	IntervalFrom	IntervalTo	CreateTimestamp	CreateUser
FHM5329	A8	76	77	1505656068	1
FHM5329	A5	81	82	1505656068	1
FHM5329	A9	81	82	1505656068	1

Variables

Although not part of the core structure, the *variables* table is by far the most important in terms of propagating the conceptual reference model. This table contains all class and classification definitions and the semantic links between the local variables and SKOS definitions, effectively tying every concept to a persistent URI. This solution provides a domain-independent extensible data model without hard-coded variables. In fact, there are no limits to its adaptability, as variables (classes, classifications or attributes) may be extended and complemented where needed to accommodate specific classification systems or thesauri of incoming data. All variables are mapped to three languages (presently Danish, English and German). A recursive relationship between variables uses the *subClassOf* field to define broader or narrower terms internally, and acts independently of higher-level SKOS terms and definitions to which they are related using persistent URIs. This effectively allows for custom hierarchies and typologies of variables to fit a very specific topic, while only linking to general overarching concepts using URIs. The support for different data types is just as dynamic and extendable. The core types cover the general: text, numbers and boolean (yes/no) and are complemented by the extended spatial data types; WKT, GeoJson and custom arrays for 3D vertices, colours, mesh faces etc. Common to them all is that they internally in the DBMS are stored as clear text, and not hidden behind proprietary file formats. An overview of the current list of variables (classes and classifications) are always available in the user-interface through the database menu (see fig. 6.17).

Table 6.13: Excerpt and structure of the *variables* table in the Archaeo database.

VariableID	SubClassOf	variableType	DataType	SkosURI	en_GB
0		class	Boolean	http://vocab.getty.edu/aat/300000810	Site
1		class	Boolean	http://vocab.getty.edu/aat/300108265	Trench
2		class	Boolean	http://vocab.getty.edu/aat/300387704	Feature
3		class	Boolean	http://vocab.getty.edu/aat/300234110	Find/Sample
4		class	Boolean	http://vocab.getty.edu/aat/300026942	Data Collection
5		class	Boolean	http://vocab.getty.edu/aat/300069084	Documentation Event
7		class	Boolean	http://vocab.getty.edu/aat/300215302	Photo
9		class	Boolean		Ortho photo
10		class	Boolean		2D spatial representation
902		class	Boolean		3D spatial representation
11		class	Boolean		Structure
1000		class	Boolean		Country
1001		class	Boolean	http://vocab.getty.edu/aat/300312281	Institution
402		dating	Boolean	http://vocab.getty.edu/aat/300106724	Stone Age
440		dating	Boolean	http://n2t.net/ark:/99152/p0r8d9c	Late Bronze Age (period 6)
21		classification	Text	http://vocab.getty.edu/aat/300054717	14C value
30	38	classification	Boolean	http://vocab.getty.edu/aat/300011793	Animal bone
31	2	classification	Boolean		Archaeological context
32	3	classification	Boolean	http://vocab.getty.edu/aat/300117127	Artefact
160		classification	Boolean	http://vocab.getty.edu/aat/300028875	Sample
525		classification	Boolean	http://vocab.getty.edu/aat/300034104	Plan drawing
526		classification	Boolean	http://vocab.getty.edu/aat/300034272	Section drawing
900		classification	SRID		Spatial Reference System
901		classification	WKT GeoJson		2.5D geometry, horizontal
903		classification	3D vertex array		3D vertices
904		classification	3D normal array		3D normals
905		classification	RGB colour array		Vertex colours
906		classification	3D UV array		3D texture coordinates
907		classification	3D face array		3D faces
208		material	Boolean	http://vocab.getty.edu/aat/300011914	Wood
38	3	material	Boolean		Bone

RelationTypes

The *relationTypes* table holds values corresponding to the properties of CIDOC-CRM. As with the *variables* table, each concept is translated to a series of languages, and furthermore derive definitions through references to CIDOC-CRM properties and SKOS concepts. Also, an inverse relation is defined to facilitate efficient queries into related entities. Relationships are defined to cover mainly hierarchical archaeological relationships; i.e. stratigraphical and physical connections.

Table 6.14: Excerpt and structure of the *relationTypes* table in the Archaeo database. Relations are partially mapped to CIDOC-CRM or CRM-ARCHAEO properties, pending CIDOC-CRM SIC approval.

RelationType	Inverse	CIDOC-CRM	en_GB
0	0	P67	Related to
1	1		Same as
2	3	AP13	Below
3	2		Over
4	5	AP5	Intersects
5	4		Intersected by
6	7	P46	Part of
7	6	AP21	Includes
9	8	P130	Shows
11	10	P69	Found in
21	22		Visualised as

Chronology

The *chronology* table links archaeological period definitions from the *variables* table to an absolute dating by start year and end year.

Table 6.15: Excerpt and structure of the *chronology* table in the Archaeo database, which maps time intervals to the *variables* table.

Chronology	Attribute	StartYear	EndYear	Remark
50	450	900	1066	Yngre Vikingetid
51	451	750	899	Ældre Vikingetid
52	452	375	1066	Yngre Jernalder
53	453	-400	-101	Mell. Førromersk Jernalder (p.2)
54	454	-500	0	Førromersk Jernalder
55	455	-100	0	Yngre Førromersk Jernalder (p.3A)

Mapping

The *mapping* table is not an explicitly required part of the data structure, but acts as an import support table, which facilitates mapping functions between external datasets and the variables defined in the *variables* table. For instance variables in

MUD web services are inter-related using corresponding identifiers in the variables table.

Table 6.16: Excerpt and structure of the *mapping* table in the Archaeo database.

Source	SourceDataset	SouceLinkTarget	SourceID	VariableID
MUD	FeatureSubcategoryTable	Subcategory	Stolpehul	146
MUD	FeatureSubcategoryTable	Subcategory	Støttestolpehul	362
MUD	FeatureSubcategoryTable	Subcategory	Tagstolpehul	363
MUD	FeatureSubcategoryTable	Subcategory	Vægstolpehul	364
MUD	FeatureSubcategoryTable	Subcategory	Bjælke	366
MUD	FeatureSubcategoryTable	Subcategory	Planke	140

Users

The *users* table manage user control according to the open data licensing, but also relates a user to each create- and delete action in the database. This facilitates tracking changes and undoing unwanted edits, and provides meta- and para data.

Table 6.17: Excerpt and structure of the *users* table in the Archaeo database.

User	Name	Institution	Username
1	Peter Jensen	Aarhus University	farkpj@cas.au.dk
2	Casper Skaaning Andersen	Aarhus University	farkcsa@cas.au.dk
3	Mads Kähler Holst	Aarhus University	mads.holst@cas.au.dk
4	Ejvind Hertz	Skanderborg Museum	ehz@museumskanderborg.dk

6.7 User interface

As stated above, development of the user-interface has been an important aspect of testing and evaluating different data modelling strategies as well as technical solutions. By direct consequence, the user-interface has become particularly important to the progression of this research. Due to the extraordinary dynamic nature and flexibility of how data are stored, very few rules exist explicitly within the data model itself. These deal exclusively with the referential integrity of data and prevents orphaned records, effectively ensuring that classifications cannot exist without an associated entity and variable. What happens beyond this is defined exclusively through queries and presented to the user through the graphical user-interface. Consequently, a series of incremental releases have already come and gone following the course of the project; starting from the ArchaeYA experimentations in Python as mentioned above, and leading to three major revisions to the development of the web-based Archaeo Framework. Development continuously progresses as new functionalities and new datasets are imported to Archaeo. Archaeo 2.1 is the most recent version at the time of writing and, while some new functionalities and additional datasets are already scheduled for upcoming versions, the following sections outline some of the core functionalities and considerations at its current stage of development. In addition to figures 3.7, 4.7 and 4.8, which also refer to the Archaeo graphical user-interface, figure 6.17 showcases many of the features described below.

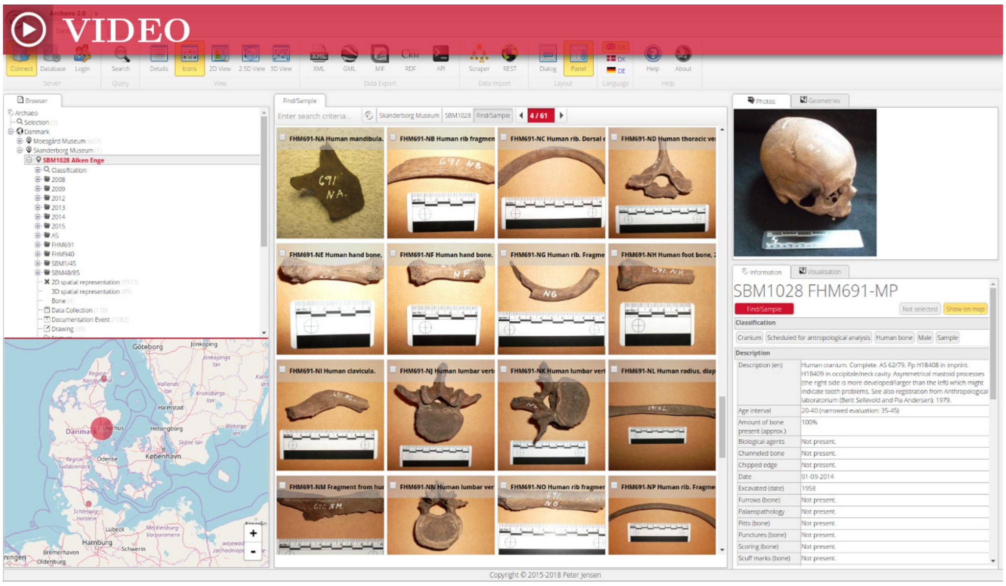


Figure 6.17: (VIDEO) The Archaeo Framework graphical user-interface.
`https://vimeo.com/259139619/51ce86b9f6`

The entry-point is: `http://archaeo.dk` or `https://archaeo.au.dk/` In order to exemplify the versatility of the data model and the adaptability of the graphical user-interface according to a broader target audience, the first screen is internally referred to as *ArchaeoExplorer* (see fig. 6.18).

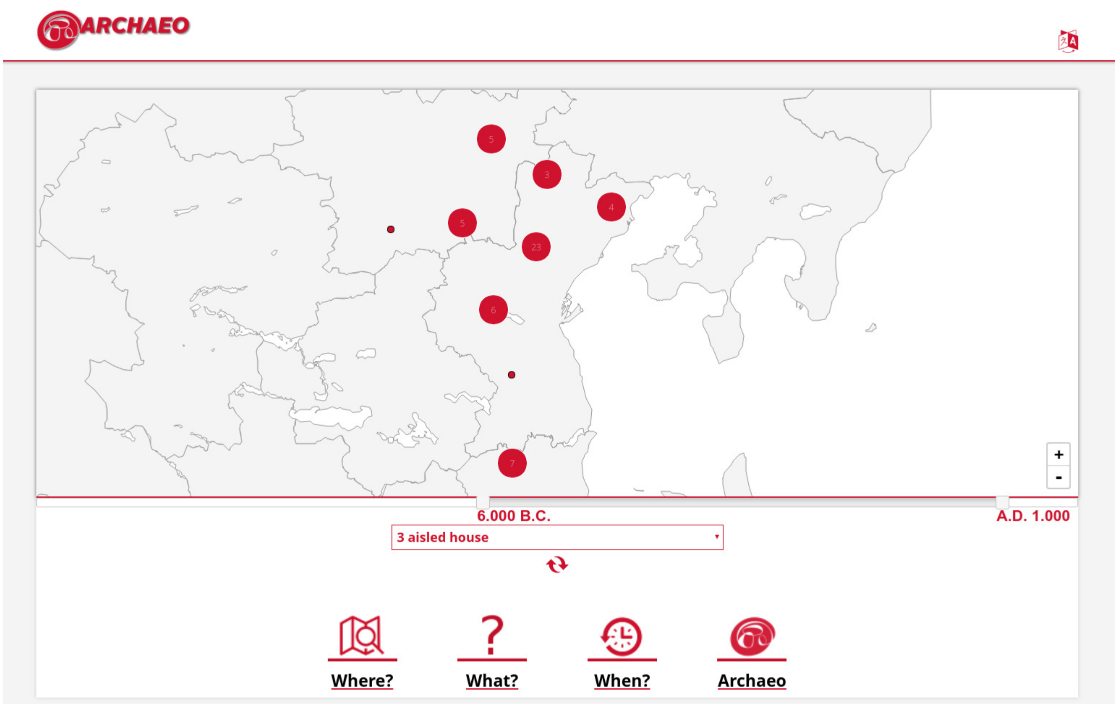


Figure 6.18: The *ArchaeoExplorer* initial user-interface.

It is in part inspired by the ARIADNE Portal, and provides a visual, interactive filtering at a site-level, according to "Where", "What" or "When". By either navigating the map, choosing a find category or using the sliders to define a time-interval, the user will experience a very dynamic approach to archaeological sites. The page is furthermore equipped with a photo-carousel of featured sites, which provides highlights to new or particularly interesting datasets. Selecting a site will bring the user to the *ArchaeoClassic* environment.

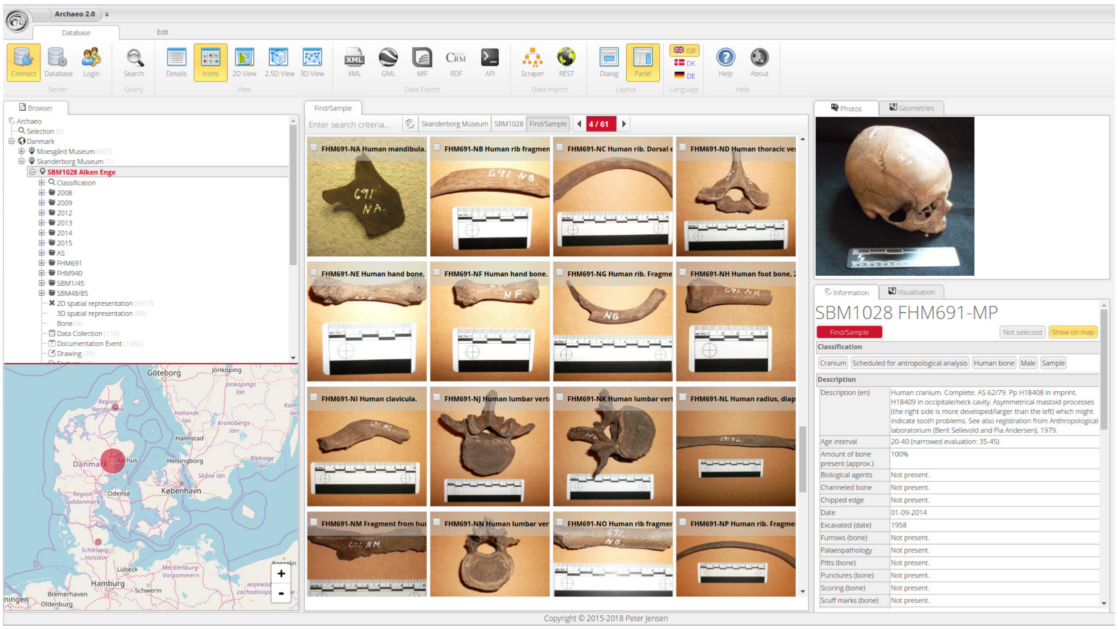


Figure 6.19: The *ArchaeoClassic* user-interface, designed to replicate the look and feel of a desktop application.

ArchaeoClassic provides more elaborate access to data, and as the name implies, it is constructed around some of the initial developments for the *ArchaeYA* development. The most prominent element is that the design aims to replicate the look and feel of a desktop application with a menu ribbon at the top of the screen and three main frames or panes of various content.

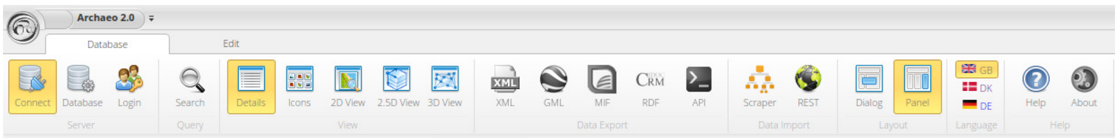


Figure 6.20: The *ArchaeoClassic* menu ribbon.

General navigation is provided by means of a hierarchical tree-view style navigation on the left-hand side, while a list-view, which either displays details or thumbnail images, is available in the centre frame. It is furthermore possible to filter by keyword. Navigating countries, archaeological institutions, sites, features or finds demonstrates the flexible hierarchical organisation, which is achieved by the EAV data model, and the domain/subdomain classification.

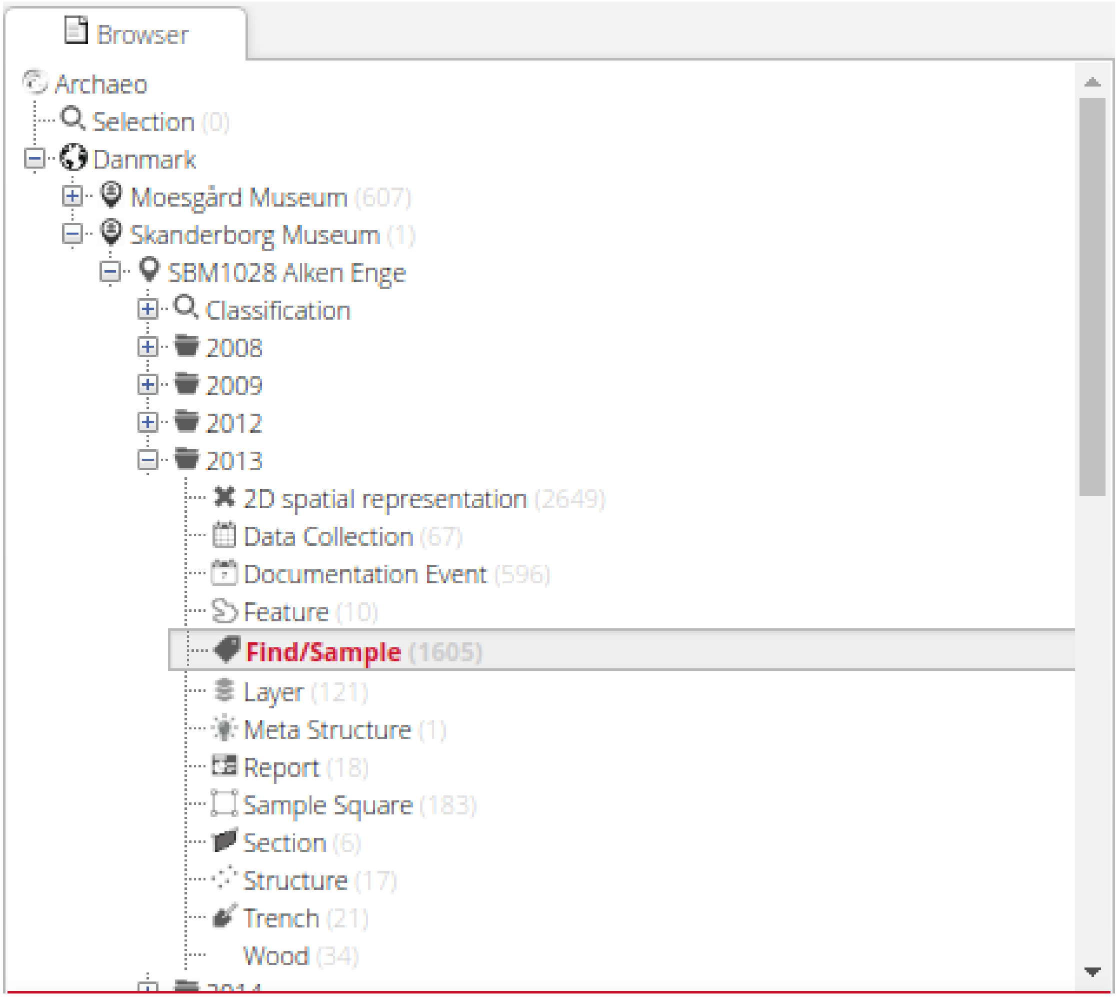


Figure 6.21: The *ArchaeoClassic* navigation tree-view.

The right-hand side of the screen is reserved for displaying the attributes for any selected item, this includes images and clickable relations to other entities or direct queries for entities of similar classification.

6.7.1 Spatial Visualisation: 2D, 2.5D, 3D ...

The spatial visualisations, including the 3D viewer, made specifically for the Archaeo Framework, were partially covered in chapter 4.5.3, which includes video demonstrating the basic functionality using Archaeo version 0.9.3. Furthermore, spatial components saturate all levels in the Archaeo Framework, emphasising their integration. To facilitate a better user experience, more complex visualisations are kept in separate viewers for 2.5D and 3D.

The 2D map visualisations are centred around the dynamic approach to the spatial data stored in the database. Each spatial element - each geometry – is stored as an individual entity in the database as either Well-Known Text (WKT) or GeoJson. Either way, all spatial data are stored as human readable text.

A key feature is that all spatial data become inherently re-conceptualised once they are imported into the Archaeo database, meaning that they are no longer confined to their original separate GIS vector layers of, for instance, features, contexts or finds. Instead, spatial elements are added to the map dynamically through either temporal, stratigraphic or conceptual queries. This means that each geometric element may appear in any combination of criteria. As an example, a particular find like a flint axe would appear in a number of queries, including “finds”, “flint”, “axe” or “Stone Age”. It is possible to add any such query to the map, and style it with different colours if needed.

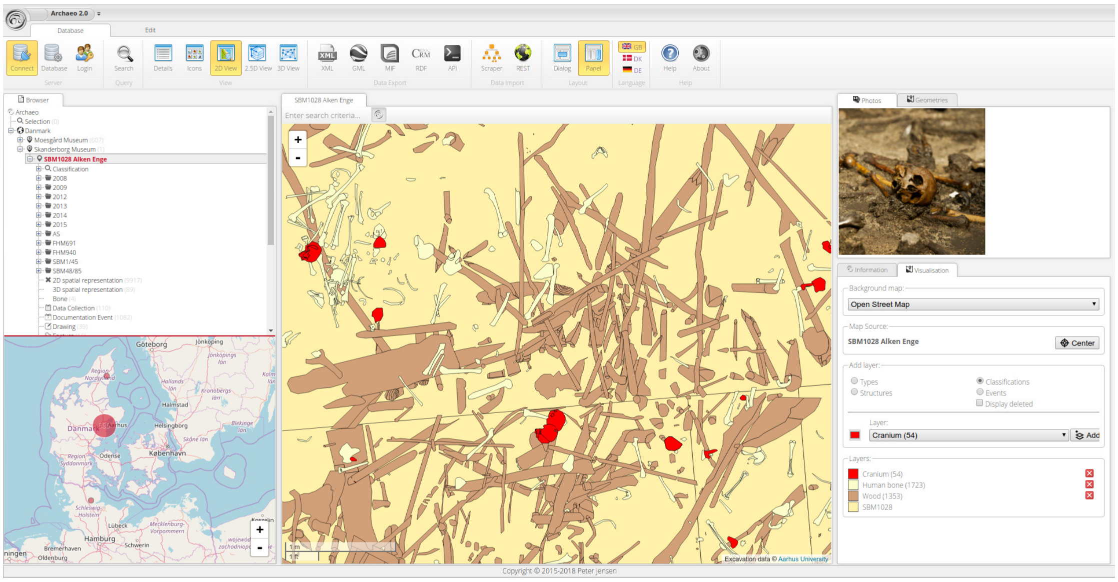


Figure 6.22: The 2D map in *ArchaeoClassic*. ”Layers” are added dynamically according to any simple temporal, stratigraphic or conceptual query.

The stratigraphic mapping is primarily handled by the Documentation Event class, which ensures that archaeological units are displayed according to the sequence by which they were recorded. Similarly, hierarchical structures are mappable. For instance, a query for a given archaeological structure (house, fence etc.) provides a visualisation of all features which are “part of” the given structure.

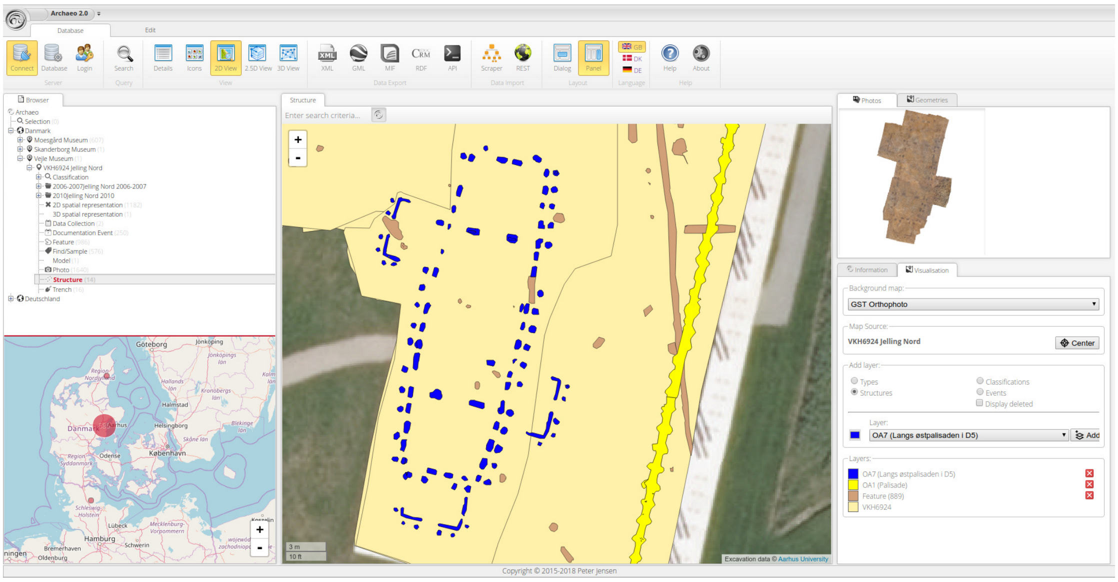


Figure 6.23: The 2D map in *ArchaeoClassic*. Structures or meta-structures consisting of several related spatial objects which "belong together" may be added as a separate "layers" dynamically. In this case the postholes that combined represent a Viking Age building in Jelling (AO7) in blue, and the palisade (OA1) in yellow.

The 3D map exemplifies the incredible potential of working with segmented 3D models. As discussed in chapter 4.4.1, the input data are classified according to a Point-in-Polygon algorithm, and subsequently stored in the database as Well-Known Text and human-readable string-arrays of vector coordinates, vector colours, texture coordinates and mesh faces (triangles). Compared to hosting separate 3D files and loading them directly to the online 3D viewer, any performance issues which arise from storing 3D data as text in the database are far outweighed by the augmented data-management capabilities provided. Separate 3D segments may be accessed beyond the scope of the 3D scene where they were recorded, and integrate as any other piece of spatial data. The 3D map also provides access to visualising the spatial hypotheses as 3D models, which was discussed in chapter 3. It allows for the exploration of how interpretations and hypotheses evolve throughout the different Documentation Events, and also provides for potentially better dissemination.

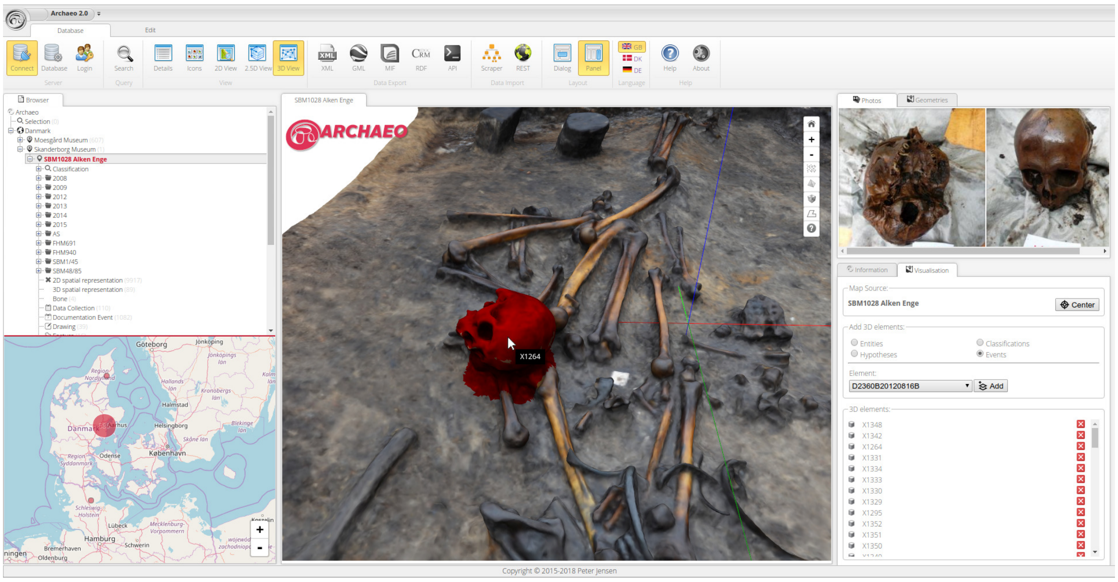


Figure 6.24: The 3D map in *ArchaeoClassic*. Segmented 3D meshes may be selected and explored, and individual segments may be added or removed from the visualisation.

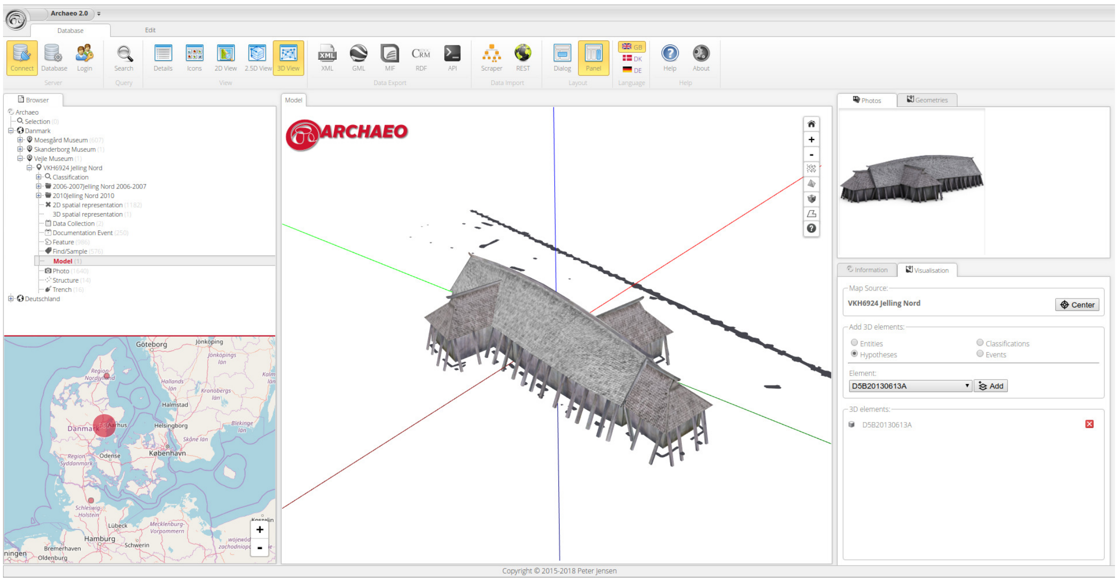


Figure 6.25: The 3D map in *ArchaeoClassic*. 3D reconstructions, stored in the database like all other spatial data, may be added to the 3D viewer to visualise the development of spatial hypotheses during and after the excavation. In this example, the Viking Age Trelleborg-type house in Jelling.

The 2.5D visualisation includes and combines all the elements which are neither only two-dimensional, yet not completely three-dimensional. This has not been one of the main concerns of this research, yet was discussed in chapter 2.5.2 and illustrated in chapter 4.5.3. The examples provided in the current iteration of the Archaeo Framework, demonstrate a clear potential of what may relatively easily be achieved by upscaling. One such example is the integration of vertical sections. The 2.5D viewer allows for a top-down, front and perspective view of vertical sections. These are stored in the database as two-dimensional geometry, but positioned in 3D space according to a point of origin and a rotation axis.

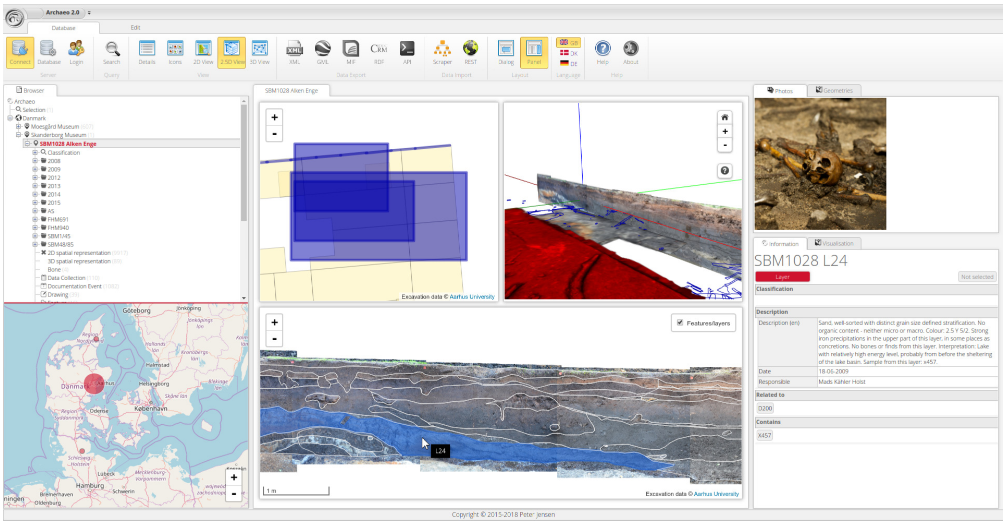


Figure 6.26: The 2.5D map in *ArchaeoClassic*. Vertical sections, stored as 2D representations (vector drawings and orthofotos), may be positioned, rotated and visualised in 3D space.

Another example is how we may dynamically assign elevation data to each Documentation Event, thereby re-establishing the stratigraphical sequence on the basis of the measurements of ground control points for the image-based recording.

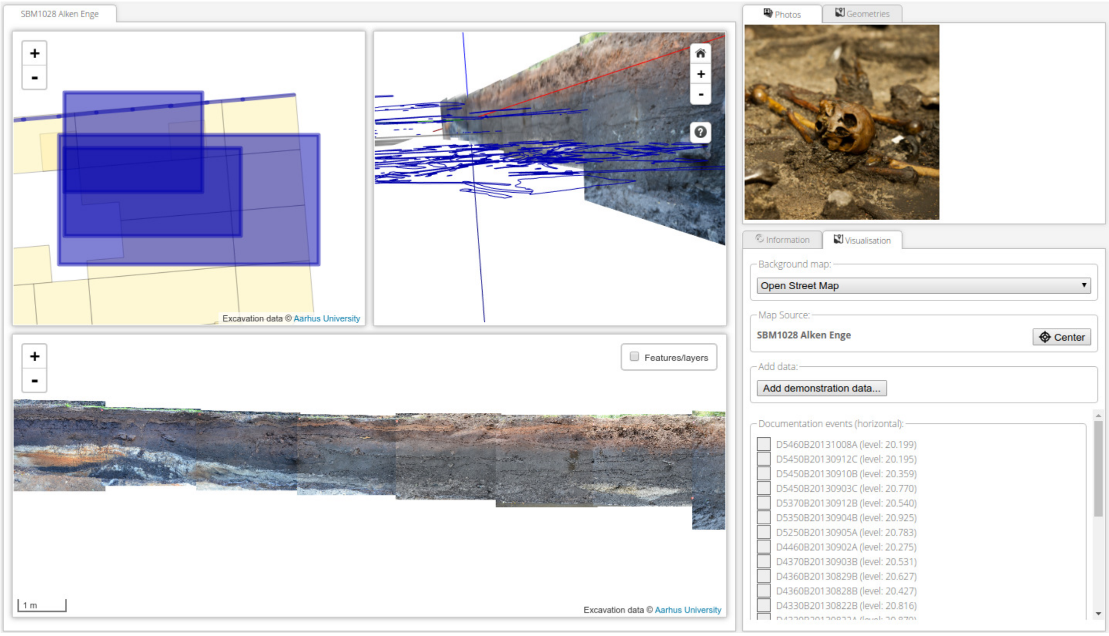


Figure 6.27: The 2.5D map in *ArchaeoClassic*. Horizontal 2D vectorisations are placed vertically according to the para data (elevation) from the Documentation Event classification to display the stratigraphic documentation sequence.

6.7.2 Querying

The Archaeo Framework provides many ways of querying data; the simplest is by direct navigation. When choosing any entity, the user is presented with all its attributes or classifications, which are clickable and provide immediate access to all other entities within the same domain (site), which have similar classification. As mentioned above, one of the strengths of employing an object-oriented approach using EAV modelling is how absence of data relate to uncertainty and knowledge. It means that entities are only assigned a particular attribute if it is explicitly present, which is why most attributes act as boolean values; they only return in queries where the attribute has been assigned.

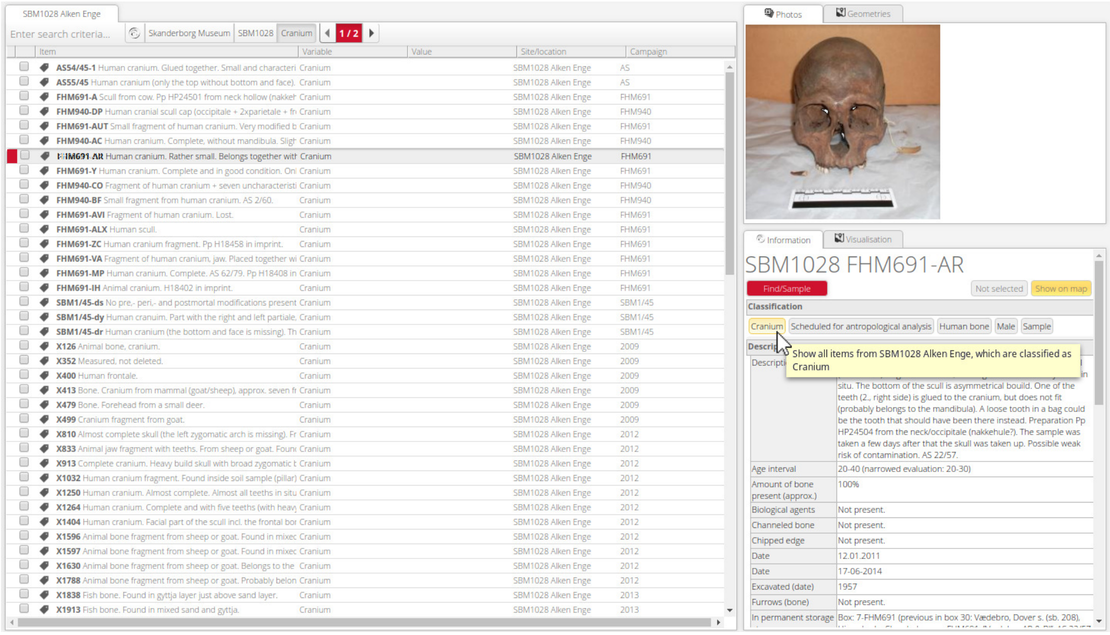


Figure 6.28: Querying *ArchaeoClassic*. By clicking on the entity classifications, a query is automatically executed which returns all other entities within the same site which share similar classification.

Apart from the filtering capabilities in the ArchaeoExplorer, a more generic search function is available in the Archaeo Framework, designed to act as a guide for the user. It includes a multi-step guide for narrowing the selection according to geography, conceptual class, and any combination of search criteria. Each search acts as an "AND"-query, meaning that all entered criteria must be met. After completing the search, the resultant entities are added to the selection. This also means that several subsequent searches effectively act as "OR"-queries on top of the already completed queries.

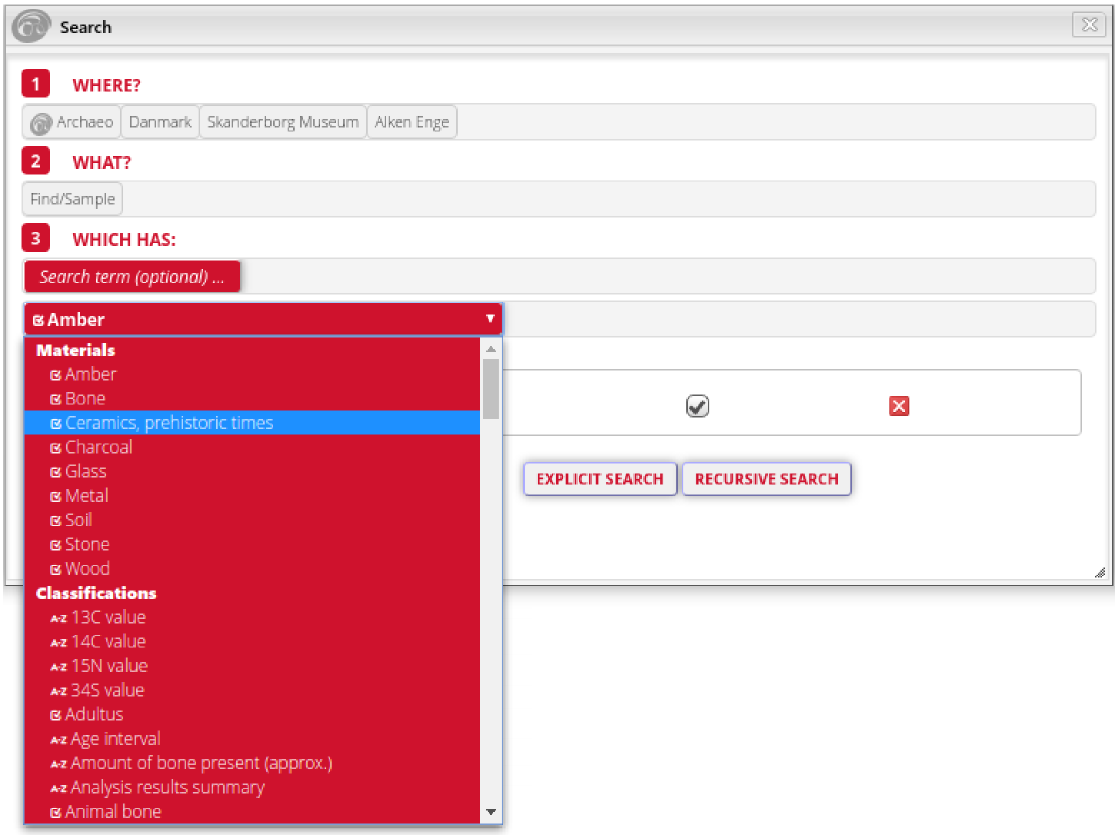


Figure 6.29: Querying *ArchaeoClassic*. The search function provides a stepwise guide to make explicit or recursive searches in the Archaeo database.

One special feature of the search function is that it provides both an "explicit" and "recursive" search mode. In the explicit search, only the exact search criteria must be met. However, depending on the source of the original data, all classifications may not be consistent or internally valid. This is the price paid for the high level of flexibility needed to accept all the heterogeneous archaeological data into the same data model. For instance, a piece of pottery may be recorded as "rim-sherd", but nowhere in the record is it stated that this entity is ceramics. However, by using the *subClassOf* information from the *variables* table, the search algorithm will traverse all parent classes of rim-sherd. Likewise, a recursive search for "ceramics" will include all subclasses of ceramics, including rim-sherd, body-sherd, handle etc. This means that we do not require an arduous pre-conceptualisation of all archaeological traditions, thesauri, nomenclatures and conceptual models to fit them into the Archaeo Framework. It also means that we may access the classification hierarchy at any level, and the inherited subclasses will provide structure for the search.

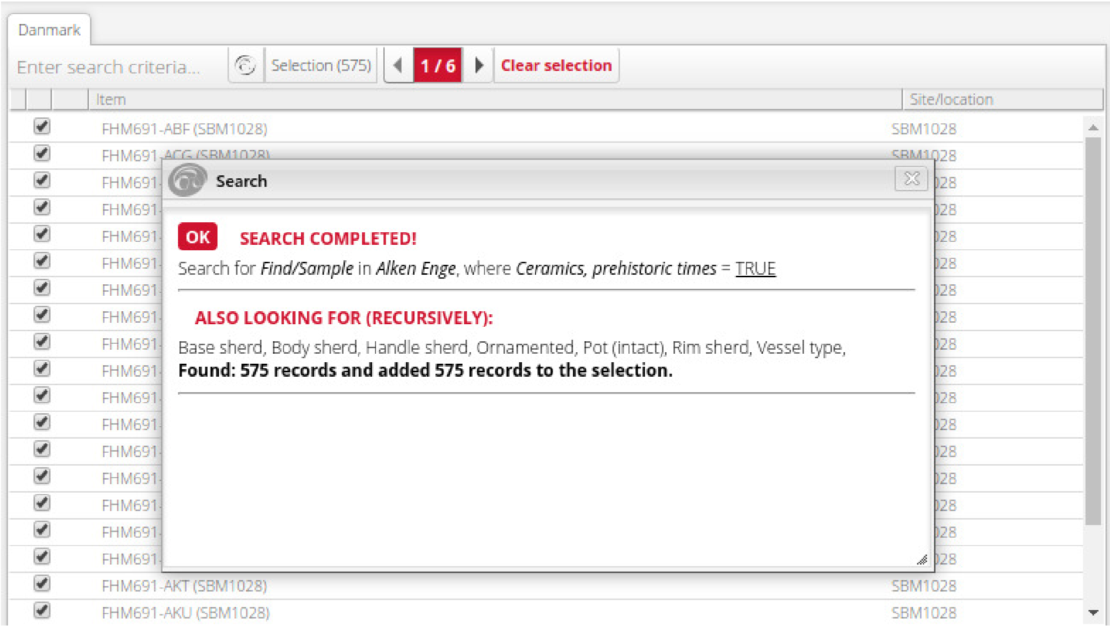


Figure 6.30: Querying *ArchaeoClassic*. The recursive search function returns all subclasses of a given classification. In this case a search for "ceramics" also returns finds classified as "rim-sherd", "body-sherd" etc.

6.7.3 Data interoperability and ArchaeoScraper

Apart from the graphical user-interface, an important precondition for a successful data model implementation is data interoperability. The potential for online collaboration was evaluated in chapter 4, yet getting data into the database in the first place is also important. For the Jelling and Alken Enge excavation projects, dedicated desktop Microsoft Access databases were used. This is a relatively common approach, and points to the need for very customisable user-interfaces. Research excavations in particular tend to have very specific research questions that require equally specific recording schemas. By the end of the Alken Enge excavations we had begun experimenting with online recording directly in the field, and it became clear that a dedicated user-interface was a high priority. Data entry in the field could become highly useful, once a dedicated user-interface was set up, and used to enforce the conceptual structure of the excavation methodology at hand. In this particular case, a user-interface for recording anthropological and osteological observations about human bones was needed. It is important to emphasise, that in the flexible and dynamic data structure of the Archaeo Framework, the data submitter is responsible for the conceptual structure of data. There are very few structural requirements for data, which means that data migration is easily accomplished, while the time and money needed for scientific augmentation of data is not an immediate requirement.

The ArchaeoScraper was introduced in chapter 4, and provides automated procedures for harvesting data from file storage. At present three modules are implemented; the module for harvesting 2D GIS data, the module for 3D semantic segmentation and a module to get all data from a file hierarchy of excavation photos.

The Archaeo Framework acts as a data repository for excavation data, and provides long-awaited integration of spatial and textual data, and for the first time it is possible to actually validate that the digital excavation plans correlate with written record at a larger scale.

As part of the implementation phase, a substantial amount of work went into developing database mappings for the web-services provided by the MUD excavation database. The SOAP-protocol allows the Archaeo Framework to communicate directly with the MUD database and query all information, currently limited to the geographic area of Moesgaard Museum.

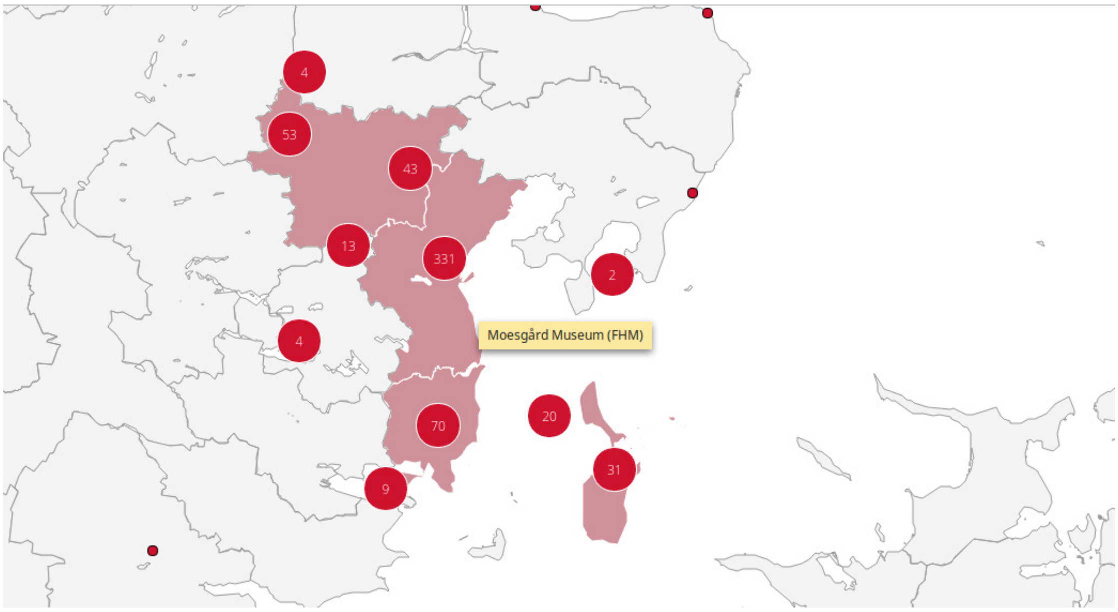


Figure 6.31: Archaeo map showing archaeological sites which are dynamically harvested from web-services (MUD) using ArchaeoScraper. In this case, c. 600 sites from the coverage area of Moesgaard Museum. The sites are mapped using clustermapping to facilitate better scalability when hundreds of sites are shown on the map at the same time.

Once data are stored in Archaeo, they are automatically mapped to online ontologies and vocabularies through the information provided in the *variables* table (see above). Specifically, all variables provide URIs to SKOS concepts. The mappings to CIDOC-CRM are automatically generated, yet not by conceptualising the entire ontology. That would defy the purpose of the simple and transparent data structure. Instead, all variables, classes and attributes are equipped with a dynamic CIDOC-CRM sentence, written in RDF syntax, including all nested levels of the complex concepts (see fig. 6.32).

```xml
<crm:E18_Physical_Thing rdf:about="http://archaeo.au.dk/SBM1028/X900">
    <crm:P45_consist_of>
        <crm:E57_Material rdf:about="http://vocab.getty.edu/aat/300011798" >
            <rdf:value>
                bone (material)
            </rdf:value>
        </crm:E57_Material>
    </crm:P45_consist_of>
    <crm:P2_has_type>
        <crm:E55_Type rdf:about="http://vocab.getty.edu/aat/300386792" >
            <rdf:value>
                Femur
            </rdf:value>
        </crm:E55_Type>
    </crm:P2_has_type>
    <crm:P43_has_dimension>
        <crm:E54_Dimension>
            <crm:P90_has_value>
                47.6
            </crm:P90_has_value>
            <crm:P91_has_unit>
                <skos:Concept rdf:about="http://www.ariadne-infrastructure.eu/measurement%20units/cm" >
                    <skos:prefLabel>
                        cm
                    </skos:prefLabel>
                    <rdf:type rdf:resource="http://www.cidoc-crm.org/cidoc-crm/E58_Measurement_Unit" />
                </skos:Concept>
            </crm:P91_has_unit>
            <crm:P2_has_type>
                <skos:Concept rdf:about="http://www.ariadne-infrastructure.eu/dimensions/length" >
                    <skos:prefLabel>
                        length
                    </skos:prefLabel>
                    <rdf:type rdf:resource="http://www.cidoc-crm.org/cidoc-crm/E55_Type" />
                </skos:Concept>
            </crm:P2_has_type>
        </crm:E54_Dimension>
    </crm:P43_has_dimension>
</crm:E18_Physical_Thing>
```

Figure 6.32: Example of an Archaeo RDF sentence, corresponding to the CIDOC-CRM ontology and using online vocabularies.

Finally, all excavation data in the Archaeo Framework are equipped with a Creative Commons license, which per-site defines how data may be used and re-used. Initially, export functions for a given archaeological site are disabled, until the content provider has approved that data may be shared as Open Data, and data may be password-protected pending final publication. As a general recommendation, data will be offered by a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International Public License.

6.8 Evaluating the data model

At its current stage of development, the Archaeo Framework and the associated data model is already proving its potential, both as a collaborative excavation tool for field recording and as a repository for post-processing and dissemination. The overall conclusion is that it provides all of the flexibility and integration needed to become an important contribution to how archaeological excavation data is managed, stored and presented. From the Danish perspective the preliminary responses from the archaeological community have only been extremely positive, and presentations at the Cultural Historical Information Meeting (2016), Archaeological GIS Forum (2016), the Danish Cultural Heritage Agency (2017) and CAA-DK (2017), have generated positive feedback. The system is scheduled for use in data dissemination for several of the larger research projects, Jelling, Alken Enge, Füsing (Dobat 2010, in press; Holst et al. 2013; Holst et al. 2018); and several museums have expressed their interest in the potential of ArchaeoScraper to provide organising, management and integration capabilities of the file-based GIS archives at the local museums. The board of the MUD excavation database has also expressed their interest in a collaboration, which includes funding and setting up additional APIs and web-services, to further the integration between the harvested GIS files and the textual excavation data from MUD.

The heterogeneous nature of archaeological data and autonomous nature of the different archaeological institutions entail an extremely dynamic conceptual data model. This fact has not changed since the initial considerations of IDEA and CIDOC-CRM 20 years ago. No matter how hard we try, we are faced with the challenge of a not-so-exact science of field archaeology, where professionals agree on surprisingly few aspects of archaeological observations and interpretations. While field archaeology in general is very enthusiastic about testing new technology and methodology, the supporters of different excavation methodologies are also inherently cautious and protectionist about doing things the "right way". This includes the risk of losing valuable excavation data by changing our ways for the sake of "going digital"; for instance by replacing drawings with digital photography and image-based 3D modelling (Morgan 2016, Morgan and Wright 2018). This also means that the requirements for how and in which form data is injected into the database are far less restricted or specific than most other systems – and kept independent of various user groups and target audiences. "All data are data", and the user-interface has the task of reaching the desired audience.

The required flexibility is achieved by isolating the conceptual reference model from the implementation model itself, and instead controlling the conceptual link through an explicit use of variables in the EAV-triple configuration. These variables are then, in turn, linked to the necessary ontologies and thesauri, but are virtually extendable beyond any one ontological model. The distinction between data model, data structure and actual implementation through the Archaeo Framework may not have been expressed explicitly, yet attention has focused on transparency and making data explicit to the end-user. Although it is definitely important to keep data and user-interface as separate entities, the implementation process has demonstrated that the user-interface should aspire to not obscure the structure of the data it seeks to present. Arguably, many of the FAIR-principles are achieved only through the development of efficient user-interfaces. This was the case of IDEA, where the limiting factors were defined by the Microsoft Access Forms framework, and it is true for the ARIADNE portal, which provides a modern user-friendly web-based interface. Data and user-interface should, however, never be interdependent. This is why the Archaeo data model is equipped with an event-based organisation and an ontology, which conceptually narrates and describes how data is understood. The data model is not determining for the user interface or the use of data, while the user interface, too, is not determining for how data is displayed or used. Instead data is exhibited or exposed in a useable form, where they may be harvested and combined using web-services and well-documented APIs. The data model is on one hand hidden for the end-user; it is hidden by the user interface, which basically handles most of the relations and navigation of records – as would any user-friendly system. On the other hand, it is extremely transparent and open, and the true strength is the simplicity of the structure. Users who wish to know how data is stored, may easily access and re-use data, knowing everything is stored as simple entity-attribute-value triples, and may fairly easily be exported to any tabular form. This also means that data may be migrated, re-interrogated and presented on almost any platform.

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7

Concluding remarks and summaries

7.1 Concluding remarks

The complexity of archaeological excavation data, with the plethora of different methodological approaches and technical applications, poses a challenge for archaeological information systems. The research presented here has consistently reaffirmed this, whilst also demonstrating that far better spatial integration is now within the reach of current technology. However, the enthusiasm for 3D recording may be premature while the necessary frameworks to handle complex spatial data are still not in place. This should, however, not discourage further method-development or experimentation in the area - on the contrary. Nonetheless archaeological excavation practice, across traditions and methodologies, demonstrably lacks a more well-defined documentation standard or end-goal. This should be aligned with the re-use of open data, rather than recording for mere archival purposes or, perhaps even worse, recording with the aim of compatibility with legacy data. In this regard, it is also important to prevent currently available technology from determining the standards by which archaeological excavations are recorded. Instead we should take advantage of recent technological developments to improve the level of detail and quality of excavation documentation in general. The increased focus on 3D GIS for archaeology in recent years is a clear indication that the necessary spatial conceptualisation for archaeological purposes is well underway, while interoperability and infrastructure for complex spatial data will most likely be important aspects of expected follow-ups and extensions for projects like ARIADNE and CIDOC-CRM in the near future.

This research also aims to avoid losing an interpretative and reflexive approach on account of photo-realistic 3D modelling. Instead, a novel approach is proposed, which combines 3D models as spatial hypotheses with field-recorded 3D models in a re-conceptualised excavation methodology where Data Collections and Documentation Events keep track of the authenticity and validity of visual abstractions. Although there are still challenges in enriching the 3D documentation produced by image-based 3D recording techniques with archaeological interpretation and classification, the research has demonstrated that it is technically possible, and this significantly adds to the usability of 3D models as carrier of semantic information. By extension, the potential for utilising 3D models in collaborative infrastructures is enormous. This not only allows knowledge exchange between researchers regardless of physical distance, but does so on far more informed grounds, by considering the realistic nature of such documentation. Moreover, a 3D infrastructure is also an immediate shortcut to easily reach a broader public through interactive visual dissemination and publishing re-usable data.

The analytical potential of field-recorded 3D data was explored by the case study of a common posthole, and as a mild provocation to the established excavation practice. It suggests a radically different approach to excavating and recording by applying micro-sectioning, something that would rarely be deemed sensible or labour-efficient. It is, however, justified by its aim to exemplify the fundamental inadequacies of a traditional surface-based archaeological recording. In working with volumes and voxels, the static 3D representation becomes dynamic and encourages further analyses during post-excavation, while shifting the research focus from surfaces and interfaces to the actual fill of archaeological features. This shows potential beyond being simply being able to rotate a 3D model on a computer screen. In combination with the experiments conducted on machine learning, the ability to use semi-automated classification of soils and fills also shows great potential, in particular in dealing with the vast amounts of image-data produced as part of Structure from Motion documentation. Herein lies some challenges of dealing with big data, and we have barely begun to explore the capability of supervised machine classification on such complicated datasets and the many other potential applications for archaeological and geological use.

The problem created by the vast amounts of accumulated spatial data is experienced by archaeological institutions and museums every day, as the file storage of GIS-related material keeps growing. Part of this research was therefore dedicated to the development of tools which could aid in the harvest of these detached spatial data, for integration into a common database. The original project title "An Archaeological Data Model for Complex Spatial Data" hints at the primary focus of the project: dealing with archaeological spatial data from the point of view of data management. Yet, as the individual chapters have demonstrated, the challenge of data integration is more than dealing with how we store data. As we have seen, there are political, economic, conceptual, methodological and theoretical barriers which prevent full integration, but then there is of course the excavating archaeologist: the professional who is expected to make sense of all observations and classifications, and develop an archaeological interpretation. How does the archaeologist react to a potentially extremely complex conceptual reference model to account for all recorded information? And where does it leave the researcher, if it requires an information scientist to access and re-use data? The research proposes a data model and structure based on two premises: data should be stored as simply and as transparently as possible, and data should be easily translatable to a well-known tabular format, recognised by field archaeologists. The other premise is that all data are data, regardless of whether they are textual, numerical, binary or spatial. This has the added benefit of all data being readable as clear text, which is also desirable from an archival viewpoint, where file-formats and media come and go. This inadvertently has the consequence of shifting much of the focus from the actual data model to the user-interface, and much of the desired functionality is enabled by the user-interface, but not explicitly defined by the data model itself. It is, in fact, a priority that neither data model nor user-interface should be determining the other.

The proposed data model is object-oriented, based on an entity-attribute-value triplestore in a relational database management system. The individual variables used throughout the database are mapped to domain-specific CIDOC-CRM classes and properties, which ensures the interoperability with existing frameworks. Additionally, variables are mapped to online SKOS resources for common vocabulary and thesauri, while services are set up for data export though different standards (GIS, XML, RDF etc.)

The implementation through the Archaeo Framework demonstrates some of the capabilities, scalability and potential of the system, and primarily the cross-queries and dynamic 2D and 3D spatial visualisations using HTML5 and WebGL are showcased.

Hopefully, the benefits of the achieved spatial integration are clearly evident, notably having all information in one system, available online for research, dissemination and data re-use. What remains largely unexplored at this point is the research potential that is immediately made possible by joining spatial and textual data in the Archaeo Framework. Things that have not previously been possible in Danish archaeology are suddenly within reach. For instance, it is possible to do spatial calculations on geometries of archaeological structures. We may easily calculate regional differences of area or sizes of anything from postholes to houses, farms and villages on basis of spatial extents of related features. We may perform compound spatial queries; for instance filtering by "Iron Age", "3-aisled longhouse", "posthole", "gable" and have immediate access to calculating cartesian lengths and orientation of houses to use for further spatial analyses or even for predictive modelling in cultural resource management.

The data model proposed in this research frames the basis for further developments of dynamic data management approaches to the integration of complex spatial data in field archaeology. It is expected to assist archaeologists in implementing better conceptualised excavation data models, and to facilitate a better understanding and use of 3D for archaeological documentation and analysis. Ultimately, the research provides access to the inaccessible dimensions of archaeological recording by joining hitherto isolated and fragmentary archaeological datasets - spatial and textual. Future areas of investigation would seek to advance this further in order to facilitate that complex spatial data persist as integrated components of archaeological data models.

7.2 English summary

This thesis finalises a 5+3 PhD project within the joint doctoral programme in Digital Heritage established in collaboration between History, Archaeology and Classical Studies, Graduate School, the Faculty of Arts, Aarhus University and the University of York.

The thesis deals with the overarching theme of spatial data in archaeological excavation recording. Spatial data are at the core of all archaeological observations, and are expressed in numerous ways, ranging from traditional hand drawings to digital two- and three-dimensional representations in Geographic Information Systems and proprietary 3D software. Yet, despite technological advances, state-of-the art digital spatial data are almost equally detached from textual archaeological interpretation as they were using conventional tools decades ago. The thesis presents a study of how technological advances influence archaeological excavation traditions and methodologies. Special emphasis is directed at exploring how the increased use of image-based 3D documentation may contribute to increased quality of field recording and, in particular, what theoretical conceptualisations and technical developments are needed to harness its full potential.

The thesis is composed of four articles, which constitute individual chapters (2-5). Each chapter covers a theme within the underlying topic of integrating spatial data in archaeology, supplemented by an introductory chapter (1), a synthesis (6) and a conclusion (7).

The first article (chapter 2) provides an introduction to the overarching research questions and their methodological and historical background. It offers some rudimentary impressions of differing excavation and recording traditions in Britain and Denmark, to critically assess the use of GIS in archaeology and the negotiation between state-of-the-art technology and archaeological practice. The article discusses how the adaptation of GIS may have contributed significantly to the detrimental effect of creating stand-alone silos of spatial data that are rarely fully integrated with non-spatial, textual data, and has acted to stifle the development of digital standards of recording by perpetuating outmoded analogue recording conventions from a previous century. The chapter outlines the potential of born-digital 3D recording technologies such as Structure From Motion (SFM), GPS, and laser scanning in current practice, while advocating for a conceptualisation of new types of data and data representation in archaeological documentation. This, however, requires changes in archaeological methodologies and workflows and that we redefine more explicitly what we actually want to do with spatial data in archaeology.

The second article (chapter 3) seeks to advance the conceptual framework of 3D models within archaeological excavation recording. 3D documentation advocates for a new workflow with a more three-dimensional reasoning, allowing for the utilisation of 3D as a tool for continuous progress planning and evaluation of an excavation and its results. Just like the general use of models to form hypotheses, it is possible to use 3D models as spatial hypotheses of an ongoing excavation. This allows us to visually realise or spatially conceptualise our hypotheses as a virtual reconstruction and to combine it with our observational data. The article presents first-hand experiences of working with 3D reconstruction and visualisations during the excavations at Viking Age site Jelling, and explores how the concept of authenticity may facilitate negotiations between visualising what we know, and what we think we know.

The third article (chapter 4) further addresses the challenges inherent to the integration of 3D documentation: specifically its inability to convey archaeological interpretations. Image-based 3D modelling is generally considered a superior tool for generating geometrically accurate and photo-realistic recording of an excavation, but does not immediately encourage reflexive or interpretative practice. This is a direct consequence of the technical limitations of currently available tools, but also reflects an archaeological methodology and spatial conceptualisation based on two-dimensional abstractions. Using the example of the excavations at the Iron Age site Alken Enge, this article takes a more technical approach to exploring how new tools developed for segmenting field-recorded 3D geometry allow embedding archaeological interpretations directly in the 3D model, thereby augmenting its semantic value considerably. This is considered a precondition for the successful integration of 3D models as archaeological documentation. Furthermore, the article explores how web-based 3D platforms may facilitate collaborative exchange of 3D excavation content and how the integration of spatial and attribute data into one common event-based data model may be advantageous. The event-based approach is used for conceptualising how digital spatial data are created, derived and evolve throughout the documentation and post-excavation process. This effectively means building a conceptualisation of excavation recording procedures and seeing them through to the data model implementation itself.

The fourth and last article (chapter 5) further explores the technologies outlined in chapters two and four. In particular, it focuses on evaluating analytical capabilities and alternative visualisation end-goals for 3D excavation recording. The chapter presents a simple case study, demonstrating the pipeline from excavating an archaeological feature, through image-based documentation and processing, to volumetric visual representation, while exploring the potential of machine learning to aid in feature recognition and classification.

Chapter six acts as a synopsis, which provides added context to the results of the preceding chapters and furthermore discusses archaeological data models in general, conceptual reference models and, finally, presents the data model and implementation developed during the research project.

The research introduces several novel approaches and technical developments aimed at aggregating the fragmented excavation data throughout the archaeological sector. This includes developing software for harvesting 2D GIS data from file storage at local archaeological institutions, functions for 3D semantic segmentation, automated processes for pattern recognition (SVM), machine learning and volumetric visualisation, and database mappings to web-services such as the MUD excavation database - all of which feed into the development of the Archaeo Framework. The online database `www.archaeo.dk` provides an implementation of the proposed data model for complex spatial field recorded data, and demonstrates the achieved data management capabilities, analytical queries, various spatial and visual representations and data interoperability functions.

The Archaeo Framework acts as a data repository for excavation data, and provides long-awaited integration of spatial and textual data in Denmark. The benefits of spatial integration are clearly evident, notably having all information in one system, available online for research, dissemination and data re-use. For the first time, it is possible to perform large-scale validation of digital excavation plans against the written record, and perform complex spatial queries at a much deeper level than merely a site on a map.

This research frames the basis for further developments of dynamic data management approaches to the integration of complex spatial data in field archaeology. The data model is expected to assist archaeologists in implementing better conceptualised excavation data models, and to facilitate a better understanding and use of 3D for archaeological documentation and analysis. Ultimately, the implementation provides access to the inaccessible dimensions of archaeological recording by joining hitherto isolated and fragmentary archaeological datasets - spatial and textual. Future areas of investigation should seek to advance this further in order to facilitate the persistence of complex spatial data as integrated components of archaeological data models.

7.3 Danish summary

Denne afhandling afslutter et 5 + 3 ph.d.-projekt indenfor rammerne af et ph.d.-program i Digital Heritage, etableret i samarbejde mellem Historie, Arkæologi og Klassiske studier, Aarhus Universitet og University of York.

Afhandlingen omhandler den manglende integration af rumlige data forbundet med arkæologisk udgravningsdokumentation. Rumlige data er kernen i alle arkæologiske observationer og kommer til udtryk på talrige måder, gennem alt fra traditionelle håndtegninger til digitale to- og tredimensionale repræsentationer i Geografiske Informations Systemer (GIS) og 3D-software. Til trods for hastige teknologiske fremskridt eksisterer de nyeste digitale rumlige data tilnærmelsesvist ligeså adskilt fra den tekstlige arkæologiske fortolkning, som ved brugen af konventionelle metoder for årtier siden. Afhandlingen præsenterer en undersøgelse af, hvordan teknologiske fremskridt påvirker arkæologisk udgravningstradition og -metode. Der lægges særlig vægt på at udforske, hvordan den øgede anvendelse af billedbaseret 3D dokumentation kan bidrage til øget kvalitet af den generelle udgravningsregistrering, og især hvilke teoretiske, konceptuelle og teknologiske tiltag der er nødvendige for at udnytte dets fulde potentiale.

Afhandlingen består af fire separate artikler, som udgør kapitlerne 2-5. Hvert kapitel behandler et tema inden for det overordnede emne vedrørende integrationen af rumlige data i arkæologisk udgravningsdokumentation, suppleret af et indledende kapitel (1), en syntese (6) og en konklusion (7).

Den første artikel (kapitel 2) giver en introduktion til de overordnede forskningsspørgsmål og den metodiske og historiske baggrund. Med udgangspunkt i en oversigt over forskellige udgravningsmetoder og dokumentationstraditioner i Storbritannien og Danmark præsenteres en kritisk vurdering af den rolle anvendelsen af GIS spiller i arkæologi samt forholdet mellem state-of-the-art teknologi og arkæologisk praksis. Konkret søger artiklen at belyse, hvordan implementeringen af GIS kan have bidraget med den utilsigtede effekt at skabe isolerede siloer af rumlige data, der sjældent optræder fuldt integreret med ikke-rumlige, tekstdata. GIS har således formået at hindre en nødvendig udvikling af digitale standarder for udgravningsdokumentation ved at fastholde forældede analoge dokumentationsprincipper fra et tidligere århundrede, målrettet papirmediet. Kapitlet skitserer potentialet i born-digital 3D-dokumentationsteknologier, såsom Structure From Motion (SFM), GPS og laserscanning i nuværende udgravningspraksis, og argumenterer for en konceptualisering af nye datatyper og former for datarepræsentation i arkæologisk dokumentation. Dette kræver imidlertid ændringer i de arkæologiske metoder og arbejdsgange og ikke mindst en mere eksplicit definition af, hvad vi rent faktisk vil anvende rumlige data i arkæologien til.

Den anden artikel (kapitel 3) søger at udvikle de konceptuelle rammer for anvendelsen af 3D-modeller i arkæologiske udgravninger. 3D-dokumentation fordrer nye arbejdsgange og tillader et mere tredimensionelt ræsonnement, der muliggør anvendelsen af 3D som et redskab til løbende planlægning og evaluering af en udgravning og dens resultater. Ligesom den generelle brug af modeller til at danne hypoteser er det således muligt at bruge 3D-modeller som rumlige hypoteser af en igangværende udgravning. Dette giver os mulighed for at visualisere hypoteser som virtuelle rekonstruktioner og kombinere dem med observationsdata. Artiklen præsenterer førstehåndserfaringer med anvendelsen af 3D-rekonstruktioner og visualiseringer under vikingetidsudgravningerne i Jelling, og undersøger hvordan begrebet autenticitet kan benyttes til at beskrive grænsefladen mellem at visualisere det, vi ved, og det vi tror, vi ved.

Den tredje artikel (kapitel 4) følger op på udfordringerne med at integrere 3D i arkæologisk udgravningsdokumentation og fokuserer på aktuelle tekniske begrænsninger og mulige løsninger. Konkret fokuseres der på de eksisterende 3D-løsningers manglende mulighed for at formidle arkæologisk fortolkning. Billedbaseret 3D-modellering anses generelt for at være et overlegent værktøj til generering af yderst detaljeret og foto-realistisk registrering af en observationssituation, men opfordrer ikke umiddelbart til en refleksiv eller fortolkende arkæologi. Dette er en direkte konsekvens af de tekniske begrænsninger ved de eksisterende værktøjer og software, men afspejler også i høj grad en arkæologisk metode og rumlig konceptualisering baseret på todimensionelle abstraktioner. Udgravningerne af jernalderlokaliteten Alken Enge benyttes i denne artikel som basis for en mere teknisk tilgang til at undersøge, hvordan udviklingen af nye værktøjer til bl.a. segmentering af 3D-geometri gør det muligt at indlejre arkæologiske fortolkninger direkte i 3D-modeller, hvorved den semantiske værdi øges betragteligt. Dette anses som en forudsætning for en vellykket integration af 3D som arkæologisk dokumentation. Desuden undersøger artiklen, hvordan web-baserede 3D-platforme kan lette samarbejde og udveksling af 3D-data blandt forskere, samt hvordan integrationen af rumlige og klassificerede data i en begivenhedsbaseret datamodel kan være fordelagtig. Den begivenhedsbaserede datamodel benyttes til at dokumentere, hvordan digitale rumlige data skabes, afledes og udvikles under en udgravning, hvilket indirekte fører til opbygningen af en konceptualisering omkring hele registreringsproceduren fra udgravning til datamodel.

Den fjerde og sidste artikel (kapitel 5) bygger videre på teknologierne beskrevet i kapitel to og fire. Der fokuseres især på de analytiske muligheder i 3D data og alternative former for visualisering og dokumentationsidealer end de fotorealistiske overflademodeller. Kapitlet præsenterer et casestudie, der gennemgår en digital udgravningsprocedure fra udgravning af et stolpehul, via billedbaseret 3D-dokumentation og bearbejdning til volumetrisk visualisering. Samtidig belyses potentialet for anvendelsen af machine learning til at identificere og klassificere arkæologiske fyldskifter.

Kapitel seks fungerer som en synopsis, der sætter resultaterne i de forudgående kapitler i en større sammenhæng og desuden diskuterer arkæologiske datamodeller og konceptuelle referencemodeller. Forskningsprojektet har bidraget med flere nye tiltag, der har til hensigt at aggregere de mange fragmenterede udgravningsdata fra store dele af den arkæologiske sektor. Dette omfatter løsninger til høst af 2D GIS-data fra fil-baseret systemer hos de lokale arkæologiske museer, funktioner til semantisk segmentering af 3D-modeller, automatiserede processer til mønstergenkendelse, machine learning og volumetrisk visualisering samt databasemapping til f.eks. Museernes UdgravningsData (MUD). Alle dele bidrager til udviklingen af online-databasen Archaeo (`www.archaeo.dk`), der repræsenterer projektets implementering af datamodellen, der er specifikt udviklet til at håndtere komplekse rumlige udgravningsdata. Databasen demonstrerer de opnåede resultater for datahåndtering, analytiske forespørgsler, forskellige rumlige og visuelle repræsentationer og datainteroperabilitet. Archaeo fungerer som datalager for udgravningsdata og leverer den længe eftertragtede integration af rumlige og ikke-rumlige data i dansk arkæologi.

Fordelene ved den opnåede rumlige integration er mange, og blot det at have al information i ét system, gjort online tilgængeligt for forskning, formidling og data-genanvendelse er et betydeligt fremskridt. For første gang er det muligt, i større skala, at udføre validering af digitale udgravningsplaner i forhold til den skriftlige registrering, og at udføre komplekse rumlige forespørgsler på et langt dybere niveau end blot prikker på et kort. Forskningsprojektet danner grundlaget for videre udvikling af dynamiske metoder til datahåndtering og integration af komplekse rumlige data i feltarkæologi, og datamodellen forventes at hjælpe arkæologer med at kunne implementere bedre konceptuelle udgravningsmodeller og -metoder, der kan bidrage til en bedre forståelse for - og brug af - 3D til arkæologisk dokumentation og analyse.

7.4 Glossary

AAT The Art & Architecture Thesaurus is a controlled vocabulary used for describing items of art, architecture, and material culture.
http://www.getty.edu/research/tools/vocabularies/aat/

ADS Archaeology Data Service, University of York. The ADS is an accredited digital repository for heritage data that supports research, learning and teaching with freely available, high quality and dependable digital resources by preserving and disseminating digital data in the long term. The ADS also promotes good practice in the use of digital data, provides technical advice to the heritage community, and supports the deployment of digital technologies.
http://archaeologydataservice.ac.uk/

AIS Archaeological Information System

API Application Programming Interface (API) is a set of subroutine definitions, protocols and tools for building application software. In general terms, it is a set of clearly defined methods of communication between various software components.

ARIADNE A European Commision funded project which aims to integrate existing archaeological research data infrastructures so that researchers can use the various distributed datasets and new and powerful technologies as an integral component of the archaeological research methodology
http://www.ariadne-infrastructure.eu/
http://portal.ariadne-infrastructure.eu/

ARK Toolkit An open source solution to archaeological project recording developed by L P:Archaeology, London.
https://ark.lparchaeology.com/

BIM Building Information Model is used to describe a collaborative process for the production and management of structured electronic information.
https://historicengland.org.uk/advice/technical-advice/recording-heritage/

Born-digital The term born-digital refers to materials that originate in a digital form. This is in contrast to digital reformatting or digitising, through which analogue materials become digital. In archaeology, digital photogrammetry, remote sensing and GPS/GNSS measurements are considered born-digital.

Box-cut An archaeological excavation technique by which an archaeological feature is sectioned by digging a box which intersects the middle of the feature. It is used to produce a vertical soil profile (see schnitt).

CAD Computer-Aided Design (software).

CIDIC-CRM An extensible ontology for concepts and information in cultural heritage and museum documentation.

Class (Database) see: *Entity*.

CRM$_{\textbf{EH}}$ An extension to the CIDOC Conceptual Reference Model, which models the archaeological excavation and analysis process by example of English Heritage.

DAI Deutsches Archäologisches Institut.
`https://www.dainst.org/`

DANS Data Archiving and Networked Services (The Hague, The Netherlands).
`https://easy.dans.knaw.nl/`

Database A logical collection of inter-related information, managed and stored as a unit.

Data model Abstraction of the real world which incorporates only those properties thought as relevant to the domain or application at hand, usually a human conceptualisation of reality.

Data stucture Representation of a data model, often expressed in terms of diagrams, lists, tables and arrays designed to reflect the recording of data in the computer code.

DBMS DataBase Management System.

DIME Digitale Metaldetektorfund, Danish national database for metal detector finds.
`https://https://dime.au.dk/`

DKC Det Kulturhistoriske Centralregister, now Fund & Fortidsminder. The Danish Sites & Monuments Records.
`http://www.kulturarv.dk/fundogfortidsminder/`

Domain or Domain ontology: concepts relevant to a particular topic or area of interest, for example, to information technology, computer languages or particular branches of science.

EAV Entity-Attribute-Value data model. A database model which employs object-oriented procedures in a Relational Database Management System (RDBMS).

Entitiy In a database, an entity may be defined as a thing capable of an independent existence that can be uniquely identified. An entity is an abstraction from the complexities of a domain. When we speak of an entity, we normally mean some aspect of the real world that can be distinguished from other aspects of the real world

Face A set of three vertices used to define a triangle in a polygon 3D mesh.

FAIR -principles. Findable, Accessible, Interoperable and Re-usable.

Fasti Online Archaeological database of the International Association of Classical Archaeology (AIAC) and the Center for the Study of Ancient Italy of the University of Texas at Austin (CSAI).
`http://www.fastionline.org/`

FISH Forum on Information Standards in Heritage (FISH) Thesauri.
`http://thesaurus.historicengland.org.uk`

GDAL Geospatial Data Abstraction Library. A translator library for raster and vector geospatial data formats that is released under an Open Source license by the Open Source Geospatial Foundation (OGC).
`http://www.gdal.org/`

GeoJson A format for encoding a variety of geographic data structures.
`http://geojson.org/`

Georeferencing Act of relating the internal coordinate system of a map or aerial photo image to a ground system of geographic coordinates. Usually done in GIS.

GEOTIFF A public domain metadata standard which allows georeferencing information to be embedded within a TIFF image file.

GLAM Galleries, Libraries, Archives and Museums.

GML The Geography Markup Language is the XML grammar defined by the Open Geospatial Consortium (OGC) to express geographical features.

GNSS Global Navigation Satellite System. Colloquially referred to as GPS.

GPS Global Positioning System. Commonly used to describe the surveying equipment used for digital recording of archaeological features. DGPS or RTK GPS employ ground based reference stations to achieve higher accuracy.

GIS Geographic Information System (software) or Geographic Information Science

Harris Matrix Used to graphically depict the temporal succession of archaeological contexts or stratigraphic sequence.

HTML5 Hyper Text Markup Language revision 5.

IADB Integrated Archaeological Database.
`http://www.iadb.co.uk/`

ICOM International Council Of Museums.
`http://icom.museum/`

IDEA Integrated Database for Excavation Analysis.

JAVASCRIPT JavaScript, often abbreviated as JS, is a high-level, interpreted programming language often used in web-pages for client-side execution. Used for navigation and visual elements (i.e. maps and online 3D viewers)

JQUERY A feature-rich JavaScript library for web-browser content manipulation, event handling, animation across a multitude of browsers.
`https://jquery.com/`

Leaflet.js An open source JavaScript library used to build web mapping applications.
`http://leafletjs.com/`

Layer In GIS, the concept of an internally related set of raster or vector data, display as a single element or strata in the GIS visualisation model.

Mesh A polygon mesh is a collection of vertices, edges and faces.

MESHLAB An open source advanced 3D mesh processing software system. Used for editing and transforming 3D data.
`http://www.meshlab.net/`

Meta data Data (information) that provide data about other data.

MUD Museernes UdgravningsData or the Museum Excavation Database is a self-governing institution, which aims to create and operate databases for archaeological survey data for Danish archaeological museums.
`http://udgravningsdata.dk/`

MySQL An open-source relational database management system (RDBMS).
`https://www.mysql.com/`

Normal (vector) The normal is often used in computer graphics to determine the orientation of a surface toward a light source for shading.

NoSQL Provides a mechanism for storage and retrieval of data that is modeled in means other than the tabular relations used in relational databases.

OGC Open Geospatial Consortium.
`http://www.opengeospatial.org/`

OGR A part of the GDAL library providing read (and sometimes write) access to a variety of vector file formats including ESRI Shapefiles, PostGIS,and Mapinfo mid/mif and TAB formats

Ontology A formal naming and definition of the types, properties, and interrelationships of the entities that exist in a particular domain of discourse.

OO Object-oriented design.

OpenGLAM Galleries, Libraries, Archives and Museum) is an initiative coordinated by Open Knowledge that is committed to building a global cultural commons for everyone to use, access and enjoy.
`https://openglam.org/`

Open Knowledge A global non-profit network that promotes and shares information at no charge, including both content and data.
`https://okfn.org/`

OpenGL Open Graphics Library is a cross-language, cross-platform application programming interface (API) for rendering 2D and 3D vector graphics.
`https://www.opengl.org/`

OWL Web Ontology Language.
`https://www.w3.org/OWL/`

Para data Data about the process by which the survey data were collected.

PeriodO A gazetteer of period definitions for linking and visualizing data.
`http://perio.do/`

Photogrammetry is the science of making measurements from photographs, especially for recovering the exact positions of surface points.

Pixel In digital imaging, a pixel is a physical point in a raster image.

PLY A computer file format known as the Polygon File Format or the Stanford Triangle Format. It is designed to store three-dimensional data and supports a relatively simple description of a single object as a list of nominally flat polygons. A variety of properties can be stored, including: color and transparency, surface normals, texture coordinates and data confidence values.

PHP A server-side scripting language designed for web development but also used as a general-purpose programming language.
`http://php.net/`

POSTGRESQL An object-relational database management system with an emphasis on extensibility and standards compliance.
`https://www.postgresql.org/`

Python A highly extendable, interpreted high-level, cross-platform programming language for general-purpose programming.
`https://www.python.org/`

QT A cross-platform application framework that is used for developing application software that can be run on various software and hardware platforms with little or no change in the underlying codebase.
`https://www.qt.io/`

Raster An image in a dot-matrix data structure, representing a generally rectangular grid of pixels, or points of colour.

RCHMS Historic Environment Scotland.
`https://www.historicenvironment.scot/`

RDBMS Relational Database Management System.

RDF Resource Description Framework. A general method for conceptual description or modelling of information that is implemented in web resources, using a variety of syntax notations and data serialization formats. It is also used in knowledge management applications (SKOS).

REGIN REgistreringsInterface. Danish archaeological data management system for cultural heritage data.
`https://www.kulturarv.dk/regin`

REST REpresentational State Transfer allows a requesting system to access and manipulate textual representations of web resources by using a uniform and predefined set of stateless operations. Similar to SOAP.

Schnitt An archaeological term used to describe the method of removing dirt from a square hole, usually for recording archaeological features in profile (see box-cut).

Semantic Web An extension of the World Wide Web through standards by the World Wide Web Consortium (W3C). The standards promote common data formats and exchange protocols on the Web, most fundamentally the Resource Description Framework (RDF).

Shape File A proprietary GIS vector file format created by ESRI.

Single Context A popular system of excavation recording and planning, particularly suited for complex deep, typically urban, archaeology. Each excavated context is given a unique "context number" and is recorded by type and organised in a vertical sequence of events.

SFM Structure From Motion is a digital photogrammetric technique for creating 3D point clouds and photo-textured meshes from digital photos.

SKOS Simple Knowledge Organization System is a W3C recommendation designed for representation of thesauri, classification schemes, taxonomies, subject-heading systems, or any other type of structured controlled vocabulary.

SOAP Simple Object Access Protocol is an XML-based protocol for the exchange of structured information across a computer network, usually via HTTP. Similar to REST.

SPARQL An RDF semantic query language, able to retrieve and manipulate data stored in Resource Description Framework (RDF) format.

SNDS Or SND Swedish National Data Services.
`https://snd.gu.se/en`

SQL Structured Query Language is a domain-specific language used in programming and designed for managing data held in a relational database management system (RDBMS).

STAR Semantic Technologies for Archaeological Resources is an AHRC funded project, in collaboration with English Heritage, applying semantic and knowledge-based technologies to the digital archaeology domain.

SVM Support Vector Machines are supervised learning models in machine learning with associated learning algorithms that analyze data used for classification based on a training dataset.

Table In a database or a GIS: a tabular view of rows and columns used to organise entities and attributes.

tDAR The Digital Archaeological Record (tDAR) is an international repository for the digital records of archaeological investigations.
`https://www.tdar.org/`

Three.js A cross-browser JavaScript library/API used to create and display interactive 3D computer graphics in a web browser. Three.js uses WebGL.
`https://threejs.org/`

TS or TST Total station (total station theodolite) is an electronic/optical instrument used for surveying and offers a theoretical higher precision than DGPS/GNSS.

UML Unified Modeling Language is a general-purpose, developmental, modelling language, intended to provide a standard way to visualize the design of a system.
`http://www.uml.org/`

URI A Uniform Resource Identifier (URI) is a string of characters used to identify a resource over a network, typically the World Wide Web.

Vector data In the context of GIS or CAD is geometry expressed as sequences or arrays of coordinates to represent points, lines or polygons.

Vertex A position (usually in 3D space) along with other information such as colour, normal vector and texture coordinates.

Voxel VOlumetric piXEL is geometry expressed as boxes in a matrix. It may be seen as a hybrid between raster and vector representations.

WebGL Web Graphics Library) is a JavaScript API for rendering interactive 2D and 3D graphics within any compatible HTML5 web browser without the use of plug-ins.

WKT Well-known text is a text markup language for representing vector geometry objects, spatial reference systems and transformations between spatial reference systems.