Documenting, Interpreting, Publishing, and Reusing

Linking archaeological reports and excavation archives in the virtual space

Derudas, Paola

ACTA ARCHAEOLOGICA LUNDENSIA SERIES ALTERA IN 8°, NO 74

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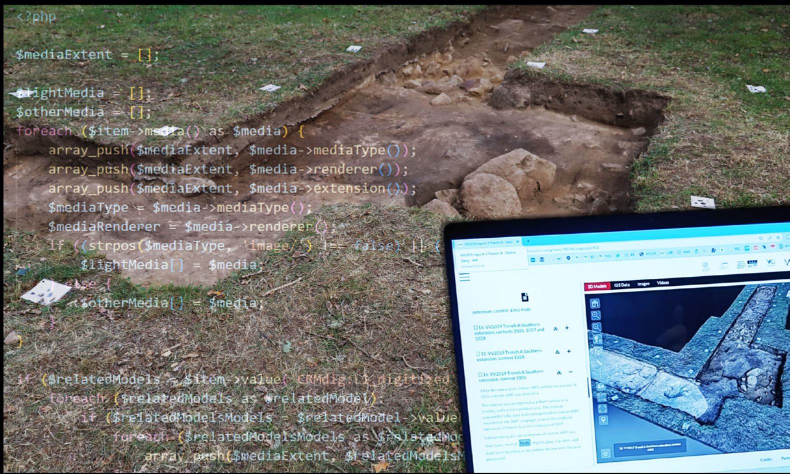
DEPARTMENT OF ARCHAEOLOGY AND ANCIENT HISTORY | LUND UNIVERSITY



Technological advancements and the increasing application of digital tools to archaeological practice are transforming the ways in which archaeologists can engage with material remains of the past. Digital methods also create new opportunities to make archaeological excavations a more collective and reflexive process. At the same time, the pace and breadth of the digital revolution in archaeology is creating a proliferation of heterogeneous datasets that are scattered in different formats across multiple repositories, potentially reducing their future re-use potentials. This PhD thesis critically evaluates the current contributions of 3D visualization and related digital tools to archaeological methods and practice. Through original research and field-based experimentation it pioneers the creation and integration of new tools, insights and knowledge that can be used to strengthen future developments in digital archaeology, rendering it more ethical and sustainable for a wide array of academic and wider societal stakeholders.

Paola Derudas is an archaeologist specializing in digital technologies. This book forms her PhD in Archaeology at Lund University, Sweden.

Joint Faculties of Humanities and Theology
Department of Archaeology and Ancient History

Acta Archaeologica Lundensia
Series altera in 8°, no 74
ISBN 978-91-89415-63-8
ISSN 0065-0994

LUND UNIVERSITY

Printed by Media-Tryck, Lund 2023
NORDIC SWAN ECOLABEL 3041 0903

Documenting, Interpreting, Publishing, and Reusing

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Paola Derudas

DOCTORAL DISSERTATION

Doctoral dissertation for the degree of Doctor of Philosophy at the Joint Faculties of Humanities and Theology at Lund University to be publicly defended on 12 May at 13.00 in LUX: C126, Helgonavägen 3, Lund

Faculty opponent
Dr Daniel Löwenborg

Organization: LUND UNIVERSITY

Document name: DOCTORAL DISSERTATION

Date of issue 12/05/2023

Author(s): Paola Derudas

Sponsoring organization:

Title and subtitle: Documenting, Interpreting, Publishing, and Reusing. Linking archaeological reports and excavation archives in the virtual space.

Abstract:

This PhD thesis examines how application of 3D visualization and related digital analytical tools is having a transformative impact on archaeological practice via improvement of visual-spatial thinking and the strengthening of conceptual understanding. However, the deployment of these new digital methods is essentially still at an experimental stage. Therefore, the thesis undertakes a critical evaluation of current progress, identifying both shortcomings and opportunities. It argues that more work is needed to systematically identify and resolve current operational challenges in order to create improved digital frameworks that can strengthen future performance across the wider discipline.

The PhD research is based on four “parallel experiments” designed to facilitate mutual enrichment and on-going refinement. Each individual experiment generated research articles, which investigate how particular 3D and digital methods can be adapted to diverse kinds of archaeological sites and features, each with unique characteristics. The articles demonstrate how particular methods can be deployed to constantly refine and improve documentation procedures, and to review and adjust interpretation during the excavation process. In total, the thesis produced five research articles and three new web-based publishing systems.

Overall, the thesis demonstrates that application, proactive evaluation and constant improvement of new 3D visualization and digital analytical tools will play an increasingly significant role in strengthening and better integrating future archaeological methods and practice. The research also generates original insights and new digital platforms that together underline the importance of applying these new digital tools across the wider archaeological discipline. Finally, the thesis cautions that digital innovation needs to be anchored in an "open science" culture, including strong ethical frameworks and commitment to FAIR principles (i.e. Findability, Accessibility, Interoperability, and Reusability) of data archiving as a key component of research design and wider societal engagement.

Key words: Archaeology, 3D digital methods, archaeological report, archaeological digital curation, online publishing systems, FAIR data, semantic web, digital humanities

Classification system and/or index terms (if any)

Supplementary bibliographical information

Language English

ISSN and key title: 0065-0994

ISBN:

978-91-89415-63-8 (print)

978-91-89415-64-5 (digital)

Recipient’s notes

Number of pages: 236

Price

Security classification

Signature

Date 2023-03-23

Acta Archaeologica Lundensia Series altera in 8°, no 74

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Cover: Image by Matilde Negrini realized using Midjourney with the prompt “network, visualization” - CC-BY 4.0

Back cover: Image by PaolaDerudas

English revised by Rebecca Montague

Joint Faculties of Humanities and Theology

Department of Archaeology and Ancient History

ISBN 978-91-89415-63-8 (print)

ISBN 978-91-89415-64-5 (digital)

ISSN 0065-0994 (Acta Archaeologica Lundensia Series altera in 8°)

Printed in Sweden by Media-Tryck, Lund University, Lund 2023

NORDIC SWAN ECOLABEL
Printed matter
3041 0903

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MADE IN SWEDEN

A Babbo, Tommaso e Francesco,
to the Past, for the Future

Table of contents

Abstract

The "Third Scientific Revolution" is ensuring that Archaeology remains at the forefront of major improvements in understanding the human past and how these impacts and legacies shape the modern world (Kristiansen, 2014). These accelerating refinements in archaeological method, theory, and synthesis are further supported by new scope for "Big Data" analysis generated by Digital Humanities. The starting point for this PhD thesis is the observation that these radical advances in Archaeology as an essentially interdisciplinary endeavour create exciting opportunities but also significant challenges across the full spectrum of archaeological method, theory, and practice. The core challenge for Archaeology is that heritage is finite and vulnerable. The very act of excavation is therefore destructive in nature — archaeologists can only research and understand the past by systematically "destroying" the material evidence that supports analysis and understanding (Barker, 1993). This predicament means that effective archaeological recovery, documentation, and archiving of data is a central obligation of the entire discipline, both for current practitioners, but also for future generations who will undoubtedly analyse and interpret legacy data with new questions and approaches.

In recent years, application of digital tools and 3D models across archaeological practice has fundamentally transformed the ways in which archaeologists engage with material remains (Galeazzi & Richards-Rissetto, 2018). While it has actively transformed excavation practice into a more collective and reflexive process (Zubrow, 2006), the ongoing Digital Revolution in Archaeology has also triggered an avalanche of new and increasingly heterogeneous datasets that are often scattered in different formats across multiple repositories, creating future problems for data archiving, accessibility, interoperability, and reusability.

This PhD thesis aims to critically evaluate the significance of transformative developments taking place at the interface between application of a raft of new digital methods and more established modes of archaeological theory, method, and practice. Specifically, it examines how application of 3D visualization and related digital analytics tools are already emerging as a crucial new component of archaeological practice by improving visual-spatial thinking and strengthening conceptual understanding (Dell'Unto & Landeschi, 2022, p. 24). However, the thesis also highlights some of the problems and pitfalls in this experimental phase of application and argues that specific challenges need to be better identified, analysed, and resolved in ways that raise overall standards and improve performance across the wider discipline.

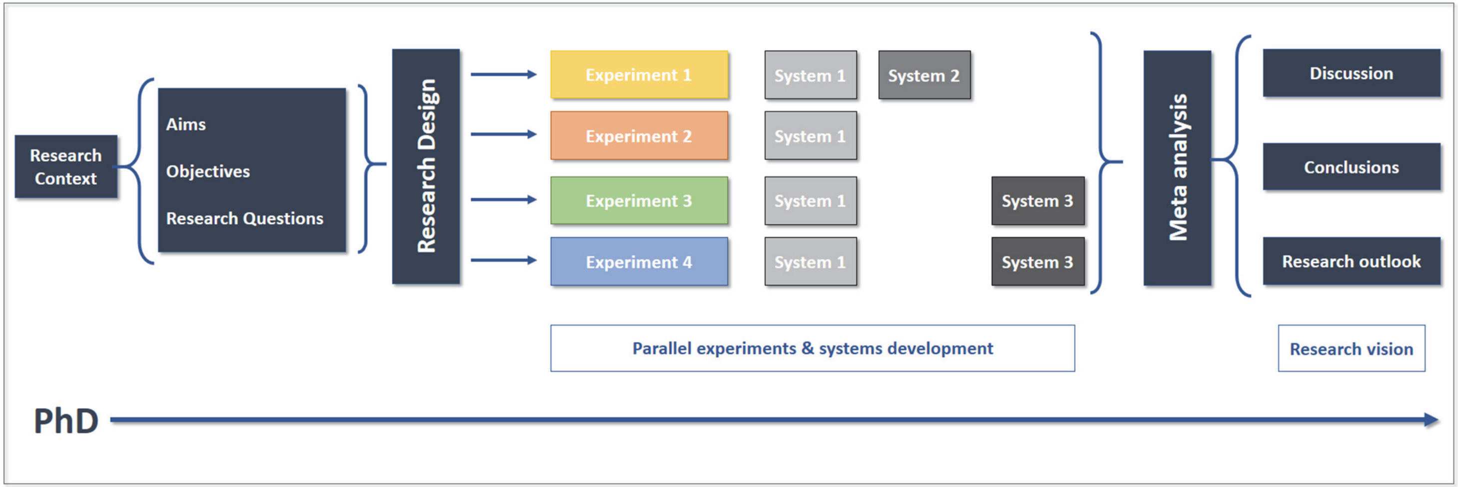


Figure 1. Thesis structure
Thesis structure and overall research design: through the research context analysis, the research problem was identified. The research design was then based on the formulation of specific questions addressed through four main parallel experiments. The experiments overlap among themselves and with the development of three web publishing frameworks. The subsequent meta-analysis allowed comparative understandings, and the definition of future research outlooks (Key: Experiment 1 is Kämpinge, yellow; 2 is Södra Sallerup, orange; 3 is Västra Vång, green; 4 is Gribshunden, blue). Image by Paola Derudas.

The thesis presents an in-depth critical evaluation of this emerging field in order to research key challenges and new opportunities. These problems and potentials are tackled via four "parallel experiments", which were deliberately designed, launched, and run in tandem, in order to facilitate mutual enrichment and on-going refinement over the course of the PhD research, which included multiple field seasons (see Figure 1). Each individual experiment generated separate research articles, which investigate how targeted application of new 3D and digital methods to specific kinds of archaeological sites and features can serve to constantly refine and improve documentation, as well as review and adjust interpretation of features during the excavation process. The thesis produced five papers and three new web publishing systems. The excavation data of the four case studies were published online through six instances of the use of these systems.

This choice of research design supports both site-specific insights and conclusions, but also creates a useful framework for a controlled meta-analysis to generate deeper and more comparative understandings that cross-cut the individual experiments. The meta-analysis confirms that the inherent flexibility of digital tools offers powerful opportunities to creatively adjust the virtual navigation of both in-field and archived excavation data, but also highlights the overarching need for future-focused data-archiving strategies to be embedded within these workflow processes.

Overall, the thesis highlights the powerful and transformative developments now taking place at the heart of archaeological research and practice. It argues that 3D methods need to be better integrated with the on-site practice of archaeological interpretation by better exploiting the potential of online platforms and editable reports that support richer narratives. These refinements will result in improved recording practices supported by real-time access to heterogeneous excavation information, including the creative use of visualization data within the process of excavation, interpretation, and eventual data archiving and publication. Finally, the novel approaches designed, conducted, and critically evaluated within the thesis demonstrate how Archaeology's Digital Revolution can actively strengthen ethical and societal commitments to the creation and archiving of open-access datasets structured according to FAIR principles. These are Findability, Accessibility, Interoperability, and Reusability.

To conclude, the thesis demonstrates that development and application of new 3D visualization and digital analytics tools is significantly enhancing archaeological methods and practice. The research contributes to debates that support fuller integration of 3D visualization within archaeological argumentation (Dell'Unto, 2018; Dell'Unto & Landeschi, 2022; Opitz, R. S. & Johnson, 2016), and also highlights the importance of balancing this with effective and ethical data-archiving practices (Börjesson & Huvila, 2019; Champion & Rahaman, 2019; Huvila, 2016) that ensure data findability, accessibility, interoperability, and reusability, thereby encouraging best practices in research data management (Wilkinson et al., 2016), in turn supporting "open science" (Richards et al., 2021).

List of papers

Paper I

Derudas, P., Dell'Unto, N., Callieri, M., & Apel, J. (2021). Sharing archaeological knowledge: The Interactive Reporting System. *Journal of Field Archaeology*, 46, 303-315.

Paper II

Derudas, P., & Berggren, Å. (2021). Expanding Field-Archaeology Education: The Integration of 3D Technology into Archaeological Training. *Open Archaeology*, 7, 556-573. De Gruyter Open.

Paper III

Derudas, P. (2021). Archaeological Publication Systems: Which route to take? A compass for addressing future development. Web3D '21: The 26th International Conference on 3D Web Technology, 1-6. Association for Computing Machinery (ACM).

Paper IV

Derudas, P., Nurra, F., & Svensson, A. New AIR for the archaeological process? The use of 3D web semantic for publishing archaeological reports.

The paper was submitted to the *Journal on Computing and Cultural Heritage,* special issue on Semantic Web and Ontology Design for Cultural Heritage. It was recommended for publication, with minor revisions. A revised version of the paper has been submitted to the editors on 01-03-2023.

Paper V

Derudas, P., Foley, B. Managing data from maritime archaeology investigations: AIR at Gribshunden.

The paper was submitted to the peer-reviewed Proceedings of the Nordic Conference for Maritime Archaeology IV.

Author's contribution to the papers

Paper I

Paola Derudas conceptualized the article and the research design; she wrote and reviewed all sections; Nicolò Dell'Unto wrote part of the "Context and Aim" section and reviewed the manuscript; Jan Apel wrote the historical information in the "Methods and Materials" section. Marco Callieri wrote part of the "Methods and Materials" section.

Author's contribution to *Paper I*

Author	Contribution to the paper
Paola Derudas	90%
Nicolò Dell'Unto	2.5%
Jan Apel	2.5%
Marco Callieri	5%

Paper II

Paola Derudas conceptualized the article and the research design; she wrote and reviewed all sections; Åsa Berggren wrote parts of all sections and most of Section 5 and reviewed the manuscript.

Author's contribution to *Paper II*

Author	Contribution to the paper
Paola Derudas	85%
Åsa Berggren	15%

Paper III

Paola Derudas conceptualized the article and the research design; she wrote and reviewed all sections.

Author's contribution to *Paper III*

Author	Contribution to the paper
Paola Derudas	100%

Paper IV

Paola Derudas conceptualized the article and the research design; she wrote and reviewed the manuscript; Federico Nurra wrote most of the “Implementing AIR” section and reviewed the manuscript; Andreas Svensson wrote part of the “The site of Västra Vång: a case study for developing digital archaeology “section and edited the manuscript.

Author’s contribution to *Paper IV*

Author	Contribution to the paper
Paola Derudas	85%
Federico Nurra	10%
Andreas Svensson	5%

Paper V

Paola Derudas conceptualized the article and the research design, and wrote and revised the manuscript; Brendan Foley wrote most of Section 2.1 and edited the manuscript.

Author’s contribution to *Paper V*

Author	Contribution to the paper
Paola Derudas	90%
Brendan Foley	10%

Abbreviations

3D GIS	3D Geographical Information System
3DHOP	3D Heritage Online Presenter
AAT	Art and Architecture Thesaurus
AIR	Archaeological Interactive Report
CIDOC	International Council for Documentation
CMS	Content Management System
CRM	Conceptual Reference Model
CSS	Cascading Style Sheets
DANS	Data Archiving and Networked Services
DBMS	Database Management System
GIS	Geographic Information System
HTML	Hypertext Mark-up Language
HTTP	Hypertext Transfer Protocol
IBM	Image-Based Modelling
IRS	Interactive Reporting System
IVS	Interactive Visualization System
JSON	JavaScript Object Notation
JSON-LD	JavaScript Object Notation for Linked Data
PHP	Hypertext Pre-processor
RDF	Resource Description Framework
REST API	Representational State Transfer Application Programming Interface
SATIFYD	Self-Assessment Tool to Improve the FAIRness of Your Dataset
SEO	Search Engine Optimization
UX	User Experience
WYSIWYG	What You See Is What You Get
WebGL	Web Graphics Library

Acknowledgements

The doctoral dissertation is a long journey that involves numerous activities such as fieldwork, data processing, analysis, study, discussions, and decision-making. My journey would not have been possible without the support of many people. They deserve all my gratitude. Their presence has been valuable and has enriched me both professionally and personally. First and foremost, I would like to express my sincere gratitude to my main supervisor, Prof. Nicolò Dell'Unto, who has also been a mentor and an advisor who has guided and encouraged me from the very beginning. He has supported my work with an enthusiastic attitude and keen interest at all stages of my research, always being available for thoughtful conversations, support, and advice, accompanying me through insightful theoretical reflections and methodological choices. Nicolò has encouraged me to find and follow my own route with conviction. I am also very grateful to my co-supervisor, Dr Marco Callieri, for his continuous support, the inspiring discussions we have had over the years, and the valuable contribution and expertise essential for the thesis's achievement and the development of the online publication systems that are a crucial component of this work. I would like to express my deepest gratitude to my colleague and friend, Dr Federico Nurra, for the inspiring discussions and methodological reflections, for always encouraging me to think outside the box, and for his treasured contribution to the development of the final output of the dissertation and the writing of the related paper.

I am incredibly grateful to Prof. Peter Jordan for taking the time and effort to read and comment on the thesis and for providing me with valuable insights and advice on how to improve its structure and readability.

I am particularly grateful to Markos Katsianis for his criticism and insightful comments at my final seminar and for providing valuable comments and feedback on the thesis. I would like to thank Dr Åsa Berggren for reading the thesis and giving me precious comments and suggestions. I would also like to thank Dr Fredrik Ekengren for the thorough overall look and type-setting of the thesis. I extend my thanks to Rebecca Montague for proofreading the thesis and for her helpful comments and suggestions.

I could not have undertaken this journey without the support of the Lund University Digital Archaeology Laboratory (DARKLab) at the Department of Archaeology and Ancient History at Lund University, which existence and international recognition motivated me to engage with digital archaeology: I want to express my gratitude to all its components for the stimulating discussions, updates, feedback, and encouragements.

I would like to thank Birgitta Lastow at the IT Department, for trusting me and for her valuable support in dealing with technical challenges.

A significant part of the research was carried out thanks to the collaboration with international institutions that hosted me, to which I want to express profound gratitude, the French National Institute of Art History (INHA) in Paris and the Visual Computing Lab at the National Research Council in Pisa. Those sojourns would not have been possible without the financial support of the Erasmus mobility program. I would like to express my gratitude to Stefan Lindgren and Carolina Larsson at the Lund University Humanities Laboratory (HumLab) for their profound expertise, kindness, and availability, their never-ending support, fruitful collaborations, and pleasant conversations.

I wish to thank all those colleagues at the department and in the various institutions with whom I have worked on the various excavation projects, co-authored the articles that make up the thesis, and who have provided me with invaluable support with data collection, management, processing, and feedback. I would like to express my gratitude to Prof. Jan Apel, who encouraged the dissertation work since the beginning, enthusiastically participated in the first experiment, and contributed to the production of the first paper. I would like to thank Andreas Svensson for his guidance in Scandinavian archaeology, for contributing to the design and development of the excavation geodatabase, for testing the Archaeological Interactive Report, and for co-authoring one of the articles. I am particularly grateful to Dr Åsa Berggren for her insightful suggestions, the inspiring conversations, and for involving me in the field courses with the students, thus allowing me to collect data for one of the PhD experiments and to write one of the papers that we co-authored. I would like to thank Dr Brendan Foley for involving me in the Gribshunden project, the most challenging experiment of my PhD, for encouraging me to experiment with data management and publication, for always manifesting enthusiastic interest and support for my work, and for co-authoring the fifth article of the dissertation.

I would like to express my gratitude to all the colleagues at the Department of Archaeology and Ancient History at Lund University, Blekinge Museum, Kalvattenkuren, and Sydsvensk Arkeologi involved in different ways in the projects that constituted the experiments of the thesis, Kämpinge, Västra Vång, Gribshunden, and in the additional case studies of Vambåsa and Domsten. I want to thank, Markus Sandekjer, Mikael Henriksson, Dr Björn Nilsson, Christoffer Sandahl, and Mikael Björk at Blekinge Museum, Siiri Irskog, and Anders Engblom at the exhibition venue Kalvattenkuren in Ronneby: they encouraged me in testing new methods and tools and provided me with a valuable support in all phases of fieldwork and data processing at the sites of Västra Vång, Gribshunden, and Vambåsa. I want to thank Helene Wilhelmson at Sydsvensk Arkeologi for involving me in the Domsten project and for her invaluable collaboration, insightful comments, and advice. I want to express my gratitude to the terrestrial and maritime archaeologists, professional divers, and volunteers I met during the many terrestrial and underwater field campaigns over the years.

The PhD journey greatly benefited from the encounter with the colleagues at the Department of Archaeology and Ancient History, whose presence, experiences, and research profoundly enhanced my PhD journey, professionally and personally. I am grateful to Dr Martin Hansson, head of the department, Prof. Henrik Gerding, assistant head of the department, and our director of studies, Dr Fredrik Ekengren, for their wise advice and generous and continuous support. I want to express my gratitude to Susanne Karlsson, Carina Andersson, Adèle Persson and Agneta Ormes for their support and assistance in dealing with administrative tasks.

I would like to express deep gratitude to the colleagues Dr Giacomo Landeschi and Danilo Marco Campanaro, who first welcomed me in Lund even before my PhD started, and who have always supported and encouraged me; the inspiring conversations with them, their methodological and technical support, and their constant availability fuelled the PhD journey from a professional and personal point of view. I want to thank Dr Fanny Kärfve, an irreplaceable office mate for the valuable advice and the long conversations on Italian and Swedish archaeology, politics, and culture. I want to express my profound gratitude to Dr Mikael Fauvelle and Greer Jarrett for being invaluable colleagues, for their availability and feedback, for the time and effort put into reading and reviewing my writings, and for the non-working time spent together. I want to thank the friendly colleagues I spent hours with beyond the working time, having lunch and conversations, enjoying the opera, and appreciating the after works and dinners: Danilo Campanaro, Dr Domenica Dininno, Dr Mikael Fauvelle, Greer Jarrett, Dr Fanny Kärfve, Dr Melda Kucukdemirci, Dr Giacomo Landeschi, Dr Mikael Larsson, Dr Hampus Olsson, and Andreas Svensson. I extend my gratitude to colleagues, current and former doctoral candidates at the Department of Archaeology and Ancient History, especially Dr Anas Al Khabour, Dr Anna Tornberg, Dr Stella Macheridis, Dr Adam Boethius, Dr Beatriz Pañeda Murcia, Dr Peder Flemestad, Sara Williamsson, Caroline Elisabeth Fisker, Erika Rosengren, Joacim Seger, Gertie Ericsson, Lena Strid, Erik Johansson, Robert Bergman Carter, Blair Nolan, and Jennifer Carey.

I would like to express a special thanks to all the new friends I met in Lund: Valeria, Alessandro, Valentina, Matilde M, Matilde F, Chiara, Eline, Miriana, Magdalena, Carmen, Barbara, Edoardo, Paul, Michael, Per, and Mattia: the light-hearted time spent in your company, even in difficult times, made me realize that it is possible to find true friends even in adult life.

I would like to thank my friends in Sardinia, Francesca and Nastassia for their constant presence and support.

Finally, I thank my beloved family for their unwavering support and belief in me. The output of this journey is dedicated to them.

1. Introduction

1.1 Archaeological reports and digital curation

This study explores the practice of archaeological reporting from a digital archaeology perspective and contributes to the current debate on the impact of 3D visualization technologies in supporting and improving archaeological practice and scholarly argumentation.

The project conceptualizes, constructs, and tests a variety of web data-management and publishing systems to study the affordances of 3D web visualization technologies to support digital archaeological curation.

Previous research has pointed out the importance of establishing a robust connection between archaeological data archives and intellectual argument (Dallas, 2015, 2016; Katsianis, 2012; Katsianis et al., 2021) avoiding the creation of isolated data silos and fragmented information (Huggett, 2016).

This doctoral project aims at addressing this gap by investigating new forms of archaeological practices based on semantically structured archives capable of supporting the archaeologists across the entire investigation process.

Although the recent diffusion of 3D spatial technology and emergence of web platforms for publishing and sharing online heritage contents has exponentially increased, most archaeologists still produce and deliver reports using publication formats that cannot accommodate the datasets produced by 3D spatial technology. It is important to note that such a rigidity in the reporting structure is also due to the need, especially in development-led archaeology, to follow strict protocols when producing the documentation, according to the various national heritage board regulations. This is the case in Sweden, where fixed rules must be followed in the structure and format of the report.

Considering the aspects mentioned above and the need to address the challenge of overcoming the gaps of disconnectivity between excavation data and report, I developed a specific research design. This consisted of an analysis of the research context in order to define the research problem. The research problem was addressed according to theoretical and methodological choices by designing and developing three web publishing systems that were used at four archaeological sites chosen as case studies for the experiments (see Figure 4). The experiments were conducted over several seasons at each site in order to test and critically assess the capacity of 3D web platforms to affect the archaeological interpretation and support the creation of multiple narratives, including archaeological reports (see Figure 3).

The results of the experiments led to the definition of an effective new practice that promotes reflexivity and multivocality and maintains a strong link between archaeological archives and scholarly argumentation.

Collaboration with researchers from different institutions was a crucial aspect of the study. The possibility of developing part of my research in different institutes allowed me to gain new perspectives and look at my work from different angles.

The research outputs (academic papers and web publishing systems) that result from this work address the various research questions posed during this doctoral project, and even though they have been published as independent works, they all result from the theoretical and methodological discussion developed during this PhD project.

All platforms developed during this work are published through Lund University's Digital Archaeology Laboratory (DARKLab) and are currently used by members of the Gribshunden and Västra Vång projects to develop their research.

This work contributes to the ongoing debate on the role of 3D visualization in support of archaeological reasoning (Dell'Unto, 2018; Dell'Unto & Landeschi, 2022) and addresses the need to implement responsible archival practice (Börjesson & Huvila, 2019; Huvila, 2016), towards open science and adherence to the FAIR principles of Findability, Accessibility, Interoperability, and Reusability that promote best practices in research data management (Wilkinson et al., 2016).

2. Research context

The theoretical framework of this dissertation was inspired by Costis Dallas and Markos Katsianis' reflections on archaeological excavation data and its information and knowledge (Dallas, 2015, 2016; Katsianis, 2012; Katsianis et al., 2021). Specifically, the starting point of this study was the concept of archaeological digital curation as "an epistemic-pragmatic activity that spans the life cycle of archaeological work", elaborated by Dallas and elicited by Gardin's *logicist program*.

Gardin's *logicist program* aimed to condense and schematize the structure of scientific constructs to make explicit the phases of the reasoning by distinguishing the primary data or "initial propositions" and the inferential operations performed on these data to establish the interpretative hypotheses (Gardin, 1980). An attempt to achieve Gardin's logicist program was made within the Archaeological Excavation Report of Rigny, by developing an interoperable logicist publication that allows for different levels of information and in-depth consultation based on the semantic web standard data exposition (Marlet et al., 2019).

Starting from Dallas' argument about the inseparability of data and scholarly argument and his definition of archaeological digital curation (Dallas, 2015), I explored appropriate ways to provide archaeologists with the opportunities to access and use the rich datasets produced at each stage of the archaeological process and to utilize them for analysis, interpretation, publication, and ultimately reuse. In order to achieve successful archaeological curation, it should be acknowledged that archaeological data management encompasses all aspects of archaeological practice (Kansa, S. W., & Kansa, 2018, pp. 81-82).

Adopting rigorous data management procedures throughout the investigation process allows for the building of comprehensive repositories and avoids the creation of data silos (Bauer-Clapp & Kirakosian, 2017; Huggett, 2016). Archaeological excavations are transient sources of new knowledge; therefore, it is crucial to store the information obtained during the investigation in an archive that is designed to encourage reuse and further analysis (Katsianis et al., 2021).

2.1 Theoretical trajectories underpinning the research

The widespread use of new digital technologies in archaeology has led to a cascade of challenges and opportunities: the emergence of new data formats, an increase in the size of datasets (Huggett, 2020) and, consequently, the proliferation of heterogeneous archives for managing the different datasets recorded during the survey.

The introduction of digitally-generated data enabled archaeologists to identify new investigative strategies, recombine and reuse archaeological datasets, and address further research questions. The proliferation of these diverse digital records has had a significant impact on archaeological practice, highlighting the importance of producing and using these datasets during fieldwork. However, despite their potential, these information is often produced and used through a skeuomorphic practice to emulate more traditional forms of documentation and archiving rather than experimenting with new practices (Taylor & Dell'Unto, 2021).

Once the investigation has been completed, the digital datasets are processed and used to interpret the evidence found in the field and ultimately to write the archaeological report. In Swedish archaeology, data collected in the field and archaeological reports are often archived in diverse repositories and made available through different (unrelated) archives (Larsson & Löwenborg, 2020).

Documenting, representing, and describing are part of the same process and should be presented and archived together. However, such heterogeneous datasets are often not linked or archived according to common standards and cannot be easily presented using visualization platforms that facilitate or encourage the development of archaeological discourses. This practice prevents their (re)use throughout the different phases of archaeological investigation, with obvious implications for the interpretation process. The use of multiple — and unconnected — repositories to manage this large and diverse data *de facto* favour data fragmentation and the creation of isolated data silos.

Dallas argues that data separation represents a relevant boundary in archaeological data management. He emphasizes the importance of maintaining a robust connection between data and scholarly argumentation, recognizing that one cannot exist without the other (Dallas, 2016). Archaeological excavation archives must be considered as dynamic and interlinked data management platforms conceived to support data reuse and multiple interpretations (Edgeworth, 2014; Katsianis et al., 2021). To achieve this goal, it is necessary to develop data management and advanced visualization platforms that encompass all aspects of archaeological practice (Kansa, E., & Kansa, 2021) that, based on the interconnection of data with its interpretations, would allow for linking such information and supporting multiple and sequential interpretations. It is essential to design systems that allow archaeologists to access such interlinked datasets throughout the investigation and refer back to each interpretative step (Katsianis, 2012). This would allow for revisiting and reusing archived information, remixing practices, and developing new investigative models (Katsianis et al., 2021, p. 2). This approach would promote efficient archaeological curation, continuous knowledge generation and multi-stakeholder engagement (Dallas, 2016, p. 180).

For these reasons, addressing issues related to data inaccessibility and long-term preservation becomes even more important as we promote the dissemination and practice of an approach based on open science and FAIR principles (Findable, Accessible, Interoperable, and Reusable).

The FAIR principles promote best practice in research data management and open access. They are an essential part of open science and are currently being adopted by several cultural heritage institutions (Wilkinson et al., 2017) to (1) promote best practices in data management and stewardship, (2) support knowledge integration, (3) support data reuse, and (4) support long-term data preservation. FAIR-compliant data are accessible to humans and machines and improve knowledge discovery, integration, and analysis (Wilkinson et al., 2016). Implementing the FAIR principles promotes the connection between archaeological datasets and scholarly argumentation, providing users with integrated and interoperable archives. This can be achieved by semantically exposing the data and making it machine-readable.

However, such an approach underlines the limitations that structured data can impose on knowledge generation: as Hacıgüzeller, Taylor and Perry suggest, the current lack of flexible infrastructures for semantically reusing the information stored in an archive is a significant problem, and for this reason it is crucial to design data management systems that are able to incorporate and embody aspects of information that are not usually included in standard archaeological archives (Hacıgüzeller et al., 2021).

Available technologies for formal data representation play an important role in this panorama, where several national and international initiatives have been directed towards more significant archaeological data management.

In Sweden, both development-led archaeology and academia are currently addressing the issue of information management (Löwenborg et al., 2021), and are continuously looking for more appropriate infrastructures and guidelines to make archaeological data more accessible. The government has committed the Swedish National Data Service (SND) and the Swedish Research Council (Vetenskapsrådet, VR) to develop national guidelines to promote open access and open data by 2026 (Jakobsson, 2021). National funding agencies are increasingly demanding open access to research data that can be stored and archived at individual institutions. Swedish universities and research institutes are addressing these issues by identifying strategies for managing long-term archiving and data availability (Gunnarsson, 2022; Jakobsson, 2021).

At the international level, the development of common practices for the management of digital archaeological data and the definition of supporting networks and research partnerships have been identified as tools to preserve the "archaeological research legacy from the digital dark age" (Richards et al., 2021). Among the initiatives at the European level, the goal of an archaeological data search portal is to enable the implementation and management of data according to a global semantic scheme as a way to overcome the lack of interoperability on the web (Berners-Lee et al., 2001; Doerr & Iorizzo, 2008).

2.2 Problem definition

Archaeology is currently in a paradigm shift triggered by the application of a wide range of new methods and approaches including digital techniques, and in the last decades its practice has changed and evolved rapidly and profoundly in terms of methods. Documentation and data management methodologies, prompted by technological advances, benefited from the diffusion of more affordable instruments, tools, and software which, within such a digital leap, appeared to be appropriate for the discipline (Evans & Daly, 2006). New workflows developed in terrestrial and maritime archaeology are based on the combination of Image-based 3D modelling (IBM) techniques and total stations, nowadays considered the primary graphic documentation tools in most archaeological investigations (De Reu et al., 2013; Dell'Unto & Landeschi, 2022; Forte, 2014; McCarthy et al., 2019; Opitz, R. S. & Johnson, 2016).

The diffusion of 3D Geographic Information Systems (3D GIS) has opened new possibilities for spatial analysis, providing the community with new 3D visual solutions that combine multiple parcels of information with the recording of three-dimensional spatial data (Dell'Unto & Landeschi, 2022). Also, the emergence of platforms for publishing and sharing online virtual cultural heritage content has boosted 3D models' circulation and stimulated the development and diffusion of such web-based platforms and online publications (Galeazzi & Richards-Rissetto, 2018; Jensen, 2018; Opitz, R. S. & Johnson, 2016; Sullivan & Snyder, 2017). However, most archaeologists continue to produce and deploy reports using publication formats incapable of including the datasets produced by 3D spatial technology.

Nowadays, archaeological reports, also referred to as grey literature or professional literature, constitute a quantitatively significant part of archaeological literature (Börjesson, 2015) and are often inaccessible. Nevertheless, they are still the most authoritative source for accessing data and information from archaeological excavations in academic and development-led investigations (Börjesson, 2017; Huvila, 2022; Larsson & Löwenborg, 2020; Lucas, 2012). For these reasons, some initiatives have emerged to increase the accessibility and visibility of this important body of knowledge (Börjesson, 2015; Gunnarsson, 2022; Larsson & Löwenborg, 2020). The information the reports contain is key to understanding archaeological archives; the archaeological community recognizes the crucial role of the reports in generating and disseminating knowledge, and many researchers emphasize their importance alongside scientific articles (Dallas, 2015; Lucas, 2012), recognizing them as a proper literary genre (Bradley, 2006).

The generally rigid and outmoded archaeological reporting practices and publication is also due to the nature of archaeological investigations, mostly performed as development-led excavations and subject to the rules of national heritage institutions, which require the documentation to be delivered in specific structures and formats. In the case of Sweden, the strong commercialization of archaeology in recent decades has led to the increased number of actors performing archaeological surveys and excavations (firms, foundations, and government agencies) and to regulations governing the reports that need to be produced based on the phases of the field archaeology process: assessment, field evaluation, and excavation (Börjesson, 2017).

In this study, I mainly refer to the excavation report, which must be produced according to scientific principles, in line with the excavation process, which, driven by research questions related to previous knowledge, must be carried out according to scientific standards and including the necessary information for administrative cultural heritage management (Börjesson, 2015, p. 1162).

Progress in Swedish archaeology in developing a digital infrastructure for managing information and data about investigated ancient and historic sites that ensures data accessibility, carried out at the National Heritage Board (NHB), has led to the recent launch of the renewed version of the Kulturmiljöregistret, the Historic Environment Record (HER). This includes a report archive (*Forndok*), a public search site (*Fornsök*), and is enriched with a tool for archaeologists to implement investigation data (*Fornreg*) (Larsson & Löwenborg, 2020). The current format of the archaeological report, usually the result of processed data as text and images, does not provide access to the underlying data — even if structured, thus limiting reusability and hindering a critical evaluation of the interpretation (Larsson & Löwenborg, 2020, p. 61).

For these reasons, it is timely to explore how the format of the archaeological report can be improved and enhanced by exploiting existing technologies based on 3D advanced web visualization and data interaction. We cannot deny that the archaeological report has also been impacted by technological advances (3D models have begun to appear as appendices to digital publications and archaeological reports), demonstrating the pressing need of incorporating more advanced visualization components (Optiz et al., 2016; Sullivan & Snyder, 2017). However, in exploring new data models for the report, it is necessary to consider the above-mentioned requirements.

Interest arose in exploring ways of enabling archaeologists to exploit the advantages of the third dimension throughout the archaeological process, as Campana points out: “All archaeologists — including those still ‘in embryo’ — have been and still are being educated to reduce and then to represent three-dimensional archaeological information in two dimensions” (Campana, 2014, p. 7). Current documentation, data management methods, and techniques all allow this third dimension to be exploited, even off-site, thereby making evident their relevance in interpreting the past. For these reasons, the role of 3D visualization as a central media for developing the archaeological interpretation, and visualising and describing a complete site interpretation has also been emphasized through the development of interactive reporting tools.

The ambition was to design a system that would allow archaeologists to take advantage of 3D visualization components for the construction of multiple site interpretations while accessing the archaeological record collected in the field (Dell’Unto, 2018, p. 66), and to develop a web platform capable of keeping the connection between raw data and their interpretation (Dallas, 2016) and making the excavation archive open, dynamic, and accessible throughout the whole archaeological process (Katsianis et al., 2021). A method was explored to combine 3D visualization with archaeological descriptions and interpretations in a unique environment, offering archaeologists the opportunity to produce more engaging reports.

The goal was to go beyond the 3D digital model, a valuable but superficial exploration of data, and add meaning and connections to it, creating interactive narratives that enhance the perception of the archaeological features’ complexity in ways impossible to reach by using traditional 2D drawings and static textual reports (Dell’Unto et al., 2017, p. 640). Recent studies have suggested a growing interest in new forms of publication in the cultural heritage sector that employ online platforms designed to include archaeological records and interactive 3D content. However, the lack of shared standards and narratives diminished the reuse of the datasets included in these publications (Schreibman & Papadopoulos, 2019), preventing their further development and diffusion.

This work identifies the archaeological report as the central narrative for accessing and exploring archaeological archives. It focuses on the definition of alternative forms of archaeological data management and reports appropriate for terrestrial and maritime archaeology that exploit the advantages of 3D online visualization and promote a digital practice that links data and interpretation.

Field investigation training activities provided an ideal environment for commencing this work. Field course excavations offer more time to test a wider range of documentation techniques, from analogue to digital, and are suitable venues for experimenting with new methods. Moreover, the unexpected positive impact that the use of the first platforms generated within field courses encouraged me to include archaeological education in the dissertation project and to reflect and discuss the pedagogical implications this work has on higher education.

It is largely recognized that the pedagogical framework should be an integral part of archaeology, as it will enable better archaeologists to be trained (Cobb & Croucher, 2014, p. 200). The chance of conducting part of the experiments with students allowed me to assess the pedagogical impact that new technologies have on courses focused on archaeological practice. This experience provided an opportunity to reflect on whether digital technologies can contribute to achieving a deep-learning approach and a sound pedagogical method through the implementation of cutting-edge technologies. Deep-learning approaches are associated with higher-quality learning outcomes and occur when the pedagogical environment encourages self-directed learning and promotes strategies that encourage discussion and questioning (Trigwell, 2006, pp. 108–113).

Even though a large body of literature recognizes the importance of technology in archaeological education (Agbe-Davies et al., 2014; Chrysanthi et al., 2012; Dell'Unto, 2018; Lock, 2003; R. Opitz & Limp, 2015) not much has been done so far to integrate 3D-based systems into field archaeology courses. However, the recent pandemic crisis has encouraged researchers to look closer at digital technology's impact on higher education (Garstki et al., 2019; Peuramaki-Brown et al., 2020), highlighting the role of 3D visualization in promoting discussion. These considerations also suggested new trajectories for the development of such a practice in the frame of field archaeology courses.

This thesis intends to develop and critically evaluate how the application of new methods and technologies based on web 3D visualization affect archaeological practice. From an initial focus on 3D visualization, it then directs attention to the process of archaeological digital curation (Dallas, 2016). Such a trajectory avoids the creation of data silos (Bauer-Clapp & Kirakosian, 2017), and makes possible the consideration of archaeological excavations as dynamic archives explorable through semantically oriented data and open to modifications and reuse (Katsianis et al., 2021). It also enables adherence to the FAIR principles (Wilkinson et al., 2016) and convergence through open science (Richards et al., 2021).

It is, therefore, necessary to identify key principles and explicit guidelines to create improved forms of best practice. Archaeologists do not yet fully understand the problems and the full potential of these new methods. For these reasons, we urgently need a critical evaluation of these methods and their application in order to identify, clarify, and resolve the issues outlined above.

For these reasons, establishing a dynamic link between the archaeological report and the excavation archive is the central element of this research. To achieve this objective, it is necessary to explore how the authoritative and trustworthy role of the archaeological report can be digitally enhanced by designing a system capable of incorporating advanced 3D visualization media and identifying interaction strategies based on the use of linked vocabularies.

The articles published as part of this project explore the impact of combining 3D visualization platforms and web data management systems and demonstrate how establishing a dynamic link between the excavation archive and the report supports data reuse and knowledge production.

The theoretical aspects underpinning this research prompted specific research questions. These are addressed through designing and implementing projects that consist of multiple investigations that are deliberately run in parallel with each other. The archaeological sites of the experiments were chosen based on their characteristics, such as chronology, objective, and research environment, in order to have a sufficiently diverse range of case studies to provide the research with a solid foundation. The experiments were conducted concurrently to facilitate reciprocal enrichment and continuous improvement over multiple excavation campaigns.

Distinct research outputs such as articles and online publication platforms describe and illustrate the experiments, exploring how the targeted application of new 3D and digital methods to different archaeological sites and environments contributes to refining and improving documentation and verifying and interpreting excavated features.

3. Aims, objectives, and research questions

The overarching goal of this project is to design and use experiments to explore, develop, and refine new practices rooted in reflexivity and multivocality through the development of new methods and technologies based on 3D visualization and semantically oriented digital tools. Specifically, it aims to investigate and critically evaluate the impact of such digital technologies based on the application of online 3D visualization tools to archaeological practice and, by extension, archaeological theory and applied methods.

To address aims and objectives, the following research questions have been formulated:

1. Can 3D reporting strengthen documentation and interpretation?
2. Can it be adjusted to specific sites and contexts, and to support field education?
3. Does it improve performance across the entire team?
4. Can it strengthen reflexivity?
5. Can it be designed and implemented in ways that strengthen FAIR?

These research questions were addressed through the experiments conducted over four primary case studies (see Figure 1) and two additional case studies.

The research design was framed around the four parallel experiments and proved helpful in developing and critically evaluating methods and digital applications. By exploring the specific requirements of each investigation, it was possible to design and develop *ad hoc* web publishing systems and test them in the archaeological practice of the case studies.

The research outputs, consisting of five papers, three web publication systems, and six instances of the use of the systems for publishing the case study excavation data, allowed me to convey site-specific insights. These results were crucial in informing and supporting the subsequent meta-analysis, which led to the identification of general elements common to all the case studies and experiments to build reusable and improvable tools.

4. Research design

To tackle the aims and objectives and answer the questions formulated above, I organized the research based on the needs, gaps, and problems of a selection of archaeological sites chosen as case studies because of specific characteristics. I conducted parallel experiments during several investigation campaigns at the sites. All are located in Sweden, between the regions of Skåne and Blekinge, and one site is maritime.

The sites have a chronology ranging from the Mesolithic to the late medieval period, and they were investigated using the single-context method (Harris, 1989) and documented using digital methods and 3D recording.

The experiments conducted at these sites overlapped and informed each other, allowing me to define documentation and data management methods and tools that could fit with and be adapted to the specific needs of each particular case study. At the same time, the possibility of testing and adapting them to other sites allowed me to make them flexible and universal.

The experiments were carried out over four and a half years and designed to determine conceptual and technical solutions for identifying and experimenting with new and efficient forms of archaeological reporting. The fieldwork provided a valuable opportunity to experiment with, test, and evaluate new methodological approaches and technological tools. In addition, the opportunity to overcome pitfalls and make new developments provided an excellent opportunity to advance the work on the basis of critical reflection and pragmatic guidance.

The PhD generated diverse research outputs, including five research articles, three web publishing systems, as well as examples of how they can be optimally deployed in specific excavation contexts. The research articles contain the experimental results and are appended to the thesis (*Papers I*, *II*, *IV*, and *V*). One of the articles was written between the experiments (*Paper III*) and provides a critical reflection on the ongoing methodological progress of current research on archaeological publication systems and offers a reorientation for the advancement of this PhD. The web publishing systems design and their development is presented; their application to the case studies is also described with a link to access them.

This chapter describes the research design of the thesis, providing an overview of the methodological aspects and delivering an account of the various experiments. It follows the linear temporal progress of the work, showing how the experiments fostered the process that allowed the advancement of the work considering theoretical, methodological, and practical components (see Figure 2).

This research design structure seems appropriate for providing a detailed account of each experiment designed for addressing the specific research questions related to each site, the methodological choices made, and the technological solutions designed, developed, or improved, and tested within the parallel experiments. It is also appropriate for providing site-specific insights and conclusions related to the specific excavation typology (see Figures 3 and 4).

Therefore, combined results from four experiments are needed to answer the identified issues. They are combined in a meta-analysis that promotes more comparative understanding and discussion. The meta-analysis allows the results of the dissertation project to be discussed, reflected upon, and critically evaluated by comparing the insights of each contribution and assessing the extent to which the study met the research objectives. The research design thus defined generates outcomes and insights of use to the wider community.

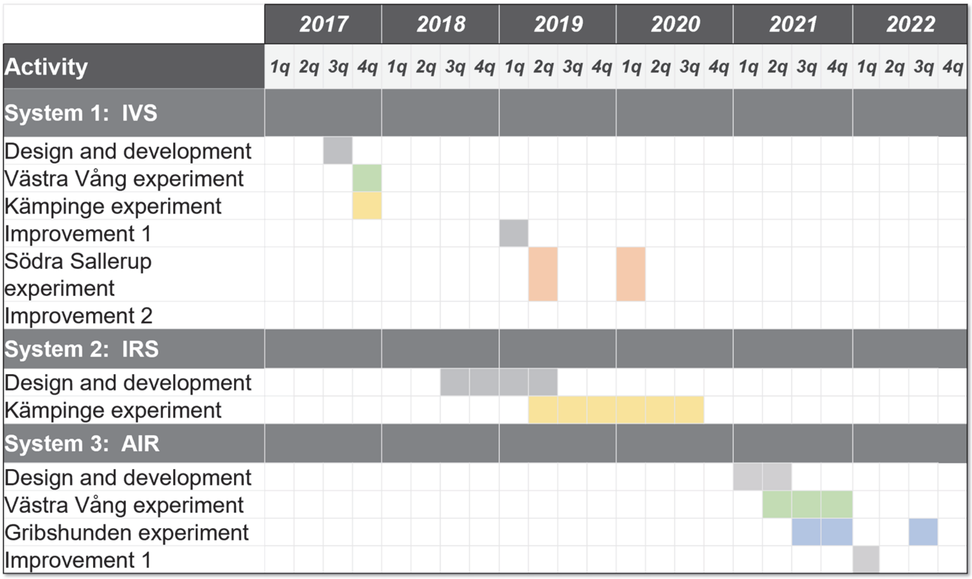


Figure 2. Thesis development timeline

The chart illustrates the advancement of the dissertation based on the activities carried out (system development, improvement, and experiments) across the different case studies studies (key: grey is system development,yellow is Kämpinge, orange is Södra Sallerup; green is Västra Vång; blue is Gribshunden). Image by Paola Derudas.

EXPERIMENT	ACTIVITY	OBJECTIVE	SITE	TIME	COMMENTS
	3DHOP experimentation for excavations	Archaeological 3D data publication and sharing	Västra Vång	Summer 2017	Accessibility to interactive 3D content positively impacted archaeological reasoning
	IVS design and test	Archaeological 3D data review, analysis, and publication	Västra Vång Kämpinge	Autumn 2018	Accessibility to interactive 3D content positively impacted archaeological data review and reasoning
Experiment 1	IRS design and test	Archaeological reporting exploiting 3D content interaction	Kämpinge	Autumn 2018	Interactive reports enhance the report structure exploiting the potential of 3D visualization components
Experiment 2	IVS development and test	3D web visualization systems to support field investigation training	Södra Sallerup	Spring 2019	Accessibility and review of archaeological 3D content supported students in reasoning and report writing
Experiment 3	IVS development and test	Definition of a documentation-to-publication workflow	Västra Vång	Summer 2019	Simultaneous 3DGIS and IVS implementation proved useful but highlighted the limitation of using multiple systems and repositories for interpretation
Experiment 2	IVS improvement and test	3D web visualization systems to support field investigation training	Södra Sallerup	Spring 2020	Accessibility and review of archaeological 3D content supported students in reasoning and report writing
Experiment 4	IVS development and test	Definition of a documentation-to-publication workflow for maritime archaeology	Gribshunden	Summer 2019	Simultaneous 3DGIS and IVS implementation proved helpful in environmentally complex (maritime) archaeology; limits of multiple systems and repositories and lack of structured accessible data
Experiment 2	IVS improvement and test	3D web visualization systems to support field investigation training	Södra Sallerup	Spring 2020	Accessibility and review of archaeological 3D content supported students in reasoning and report writing
Experiment 3	AIR design, development, and implementation with data from previous campaigns	Definition of a documentation-to-publication workflow	Västra Vång	Spring 2021	3D visualisation combined with structured data allowed the interlinking of data and archaeological argumentations
Experiment 4	AIR implementation with data from previous campaigns	Definition of a documentation-to-publication workflow for maritime archaeology	Gribshunden	Spring 2021	Issues with the use of AIR for the multi-temporal representation of elements belonging to the same layer
Experiment 3	AIR as the primary documentation tool	Assessing the use of AIR in real-time as the primary management tool	Västra Vång	Autumn 2021	Live use of AIR represented an advance in archaeological practice providing archaeologists with the complete multi-media format documentation at their disposal
Experiment 4	AIR as the primary documentation tool	Assessing the use of AIR in real-time in maritime archaeology	Gribshunden	Summer 2022	Live use of AIR for maritime archaeology documentation and data management promotes a data-curation approach that encompasses the whole excavation practice

Figure 3. Experiments, activities, objectives, and evaluation
Details of experiments in terms of activities, objectives, and evaluations: how these map onto case studies (key: yellow is Kämpinge, orange is Södra Sallerup; green is Västra Vång; blue is Gribshunden). Image by Paola Derudas.

4.1 Design of cross-experimental fertilization

The dissertation project is articulated across six archaeological sites and eleven different excavation campaigns that span in time from the Mesolithic to the late medieval period, and from terrestrial to maritime environments. The diversity of investigation environments provided the optimal opportunity for experimenting with various data management and online publication methods.

When conducting the experiments, specific criteria guided the selection of the sites: location, chronology, excavation characteristics, excavation methods, and documentation. All the sites included in the study are located in Sweden, with three terrestrial excavations, and one maritime. One case study is based on 3D data reuse, while the others use data from ongoing projects. The chronology ranges from prehistory to the late medieval period; the excavation method, in the case of the terrestrial excavations, uses the single context. All investigations were documented using digital methods (see Figure 4).

The experiments' duration spans four and a half years, which roughly corresponds to the duration of the study: multiple field seasons at the sites from 2018 to 2022 provided an appropriate environment for the experiments, allowing technological solutions to be designed, developed, and tested.

The experiments' evaluation helped identify pitfalls to be overcome and the potential for further development. New developments could then be applied to the data from another case study campaign, activating a continuous process of design–development–experiment–evaluation. This approach enabled synergetic cross-pollination among the experiments to the benefit of all.

Each case provided the possibility to test different aspects of this research and — most importantly — design and prototype various publishing systems for assessing new forms of archaeological reporting and data reuse. Furthermore, it allowed the assessment of the impact that new 3D media have in the knowledge production process and how the introduction of such tools encourages the development of novel practices.

4.1.1 Design of Kämpinge

The first case considered in this study was the archaeological site of Kämpinge, a Mesolithic site in south Sweden (*Paper I*). The site was investigated prior to the beginning of this doctoral project, across four field campaigns (2014–2017) by a team of Lund University archaeologists and masters' students, who used 3D recording techniques as the primary recording system (Dell'Unto et al., 2017). The datasets produced and the methodologies developed for recording the archaeological information have been essential resources for this project in developing experiments and mapping the limitations and potential of (re)using the 3D datasets recorded during the field investigation to construct archaeological reports.

The experiments undertaken in this case study led to the design and development of the Interactive Reporting System (IRS), a platform based on the 3D Heritage Online Presenter (3DHOP).

3DHOP is an open-source framework for the creation of interactive web presentations of high-resolution 3D models, oriented to the cultural heritage field (Potenziani et al., 2015). Unlike other systems, 3DHOP allows for a high degree of customization, and since its initial deployment around 2014, the system is still considered one of the most viable solutions within the cultural heritage sector (Ekengren et al., 2021).

The Interactive Reporting System was designed primarily to test the capacity of 3D data visualization platforms for supporting the creation of new dynamic forms of archaeological reports. In addition, the system was also used to assess the potential of HTML5 3D graphics subset (WebGL) to support archaeologists while reinterpreting archaeological features in the digital space.

The system was used primarily by Professor Jan Apel of the University of Stockholm, Sweden, the Kämpinge excavation leader, to revisit the site documentation, assess different interpretation hypotheses, and (re)write the archaeological reports of each excavation campaign later made available through IRS.[1] It was also employed during the pandemic for training masters' students in archaeological field practice at the University of Stockholm.

The user group confirmed that the system functioned well and provided further useful feedback: the possibility of using diachronic sequences of 3D models to revisit the investigation process facilitated the identification of further archaeological information and, consequently, the construction of new hypotheses.

Further experiments were necessary to assess the platform's capacity to impact field practice and to identify a strategy to orient the system towards a more FAIR-compliant data model. The work developed in Kämpinge relied on data previously generated by a heterogeneous group of scholars (students and researchers). At this stage of the research, it was necessary to determine the platform's ability to promote knowledge production during the field investigation. Did the system only function during post-excavation activities? How would the use of such a system during the field investigation affect the field practice, and consequently, interpretation?

[1] https://www.darklab.lu.se/digital-collections/dynamic-excavation/kampinge/

AIMS	DETAILS	METHODS	OUTPUTS AND INSIGHTS strengths, weaknesses, recommendations
Kämpinge			
How effective is IRS in reusing 3D data from completed excavations to write the site report?	Mesolithic site in south-western Skåne; identification of intact cultural layer; single-context method	3D documentation; digital data management and online publication	Effectiveness of IRS to write report with reused 3D data; using it afterwards limits its potential of performing a reflexive approach; the system should be tested live during excavations
Södra Sallerup			
How effective is IVS in supporting excavation data analysis and interpretation and contributing to a deep learning approach to field education?	Stratified Bronze and Iron Age deposits; training of undergraduate students in fieldwork activities employing digital technologies; single-context method	analogue and digital documentation; digital data management and online publication	IVS effectively supports undergraduate students in analysing and interpreting excavation data; the missing connection between data and report limits its benefits; structuring data and linking data and argumentation should be developed
Västra Vång			
How effective is AIR as a tool for documentation, management, and publication of data and reports in single-context-methods excavations?	Iron Age central place and settlement in the region of Blekinge; comprehend the hill-site's stratigraphy better; single-context method	analogue and digital documentation; digital data management and online publication	AIR proved an effective tool for documenting, managing, and publishing data and reports single-context-method excavations; AIR could be tested in more complex environments and incorporate diverse data from other specialists
Gribshunden			
How effective is AIR as a tool for documentation, management, and publication of data and reports in maritime excavations?	Late medieval wreck of the Danish king Hans' flagship sunk in 1495 in Blekinge; analysis of the ship's role in late medieval northern Europe; underwater excavation with a venture dredge	3D documentation; digital data management and online publication	AIR proved an effective documentation tool for excavations in more challenging environments such as the maritime; AIR could be further developed for addressing the requirements of multidisciplinary excavations and incorporate data from specialists involved in the projects

Figure 4. Aims, methods, and preliminary evaluation
The scheme illustrates the aims of each case study, describes the details and methods developed, identifies their strengths and weaknesses, and makes recommendations. Image by Paola Derudas.

To address these questions, the ideal scenario would have been performing a new excavation campaign in Kämpinge to test the system's capacity to empower archaeologists working in the field. Unfortunately, this was impossible, so new case studies were identified to test such an approach.

4.1.2 Design of Södra Sallerup

Previous tests had been conducted with 3DHOP (Derudas et al., 2018), which in 2017 led to the development, at the archaeological site of Västra Vång (Blekinge), of the Interactive Visualization System (IVS). The IVS is an online 3D platform designed to share the sequences of archaeological contexts and features encountered during the field investigation with specialists working off-site. At Västra Vång, in 2017, archaeologists working in the field were not involved in the experiment, and they did not use the system during the excavation.

The opportunity for a new experiment came in 2019 when a new excavation was begun at the archaeological site of Södra Sallerup (Skåne). In this new excavation, the entire team, composed of students and teachers, used the Interactive Visualization System as the primary online visualization platform for engaging with the graphic documentation during the excavation and post-excavation activities. This experiment provided important insights concerning how field archaeologists interact and use the system to support the construction of narratives (*Paper II*).

The field experiment was an excellent opportunity to test the limitations and potential of web-based technologies in support of field practice and archaeological training. Before commencing the experiment, models and structures for supporting the students during the archaeological field training were identified. Particular emphasis was placed on determining how the use of such a tool impacted the archaeologists' perception of the records encountered during the investigation.

By the end of each field investigation campaign, the data were implemented in the IVS and then used to review the material, make illustrations, and access the previous year's graphic documentation. The platform was employed to explore the excavation's progress and to identify relations among contexts and artefacts retrieved during the two investigation campaigns. At the end of the field campaigns, the students used the system to (1) analyse the excavation units, (2) review the previous year's documentation, and (3) produce sections and plans to use in the archaeological report.

These experiments provided essential indications on how to progress the research. If, on the one hand, this approach proved the capacity of 3D web visualization platforms to support field investigation and knowledge production, on the other, it revealed the inability of the system to establish a direct connection with the entire excavation archive, with the evident consequence of not solving issues connected to data fragmentation (the excavation data repository-database was not directly linked to the 3D web visualization system). These experiments also highlighted the need to explore alternative routes to design adequate solutions to incorporate the whole excavation datasets and all their data formats in a unique space, an open and interconnected 3D archive capable of hosting and linking the excavation data management system with digital archaeological reports.

To achieve such a goal, several projects dealing with 3D web visualization and cultural heritage archives were analysed and reviewed (*Paper III*). This study illustrated the progress of the work within various research projects mainly producing advanced online 3D data repositories designed for supporting spatial analysis (Jensen, 2018; Richards-Rissetto & von Schwerin, 2017). Less explored appeared to be systems designed to support archaeologists in constructing dynamic archaeological reports that can be used at any stage of the investigation and can facilitate and promote access to more extensive sets of archaeological data. The results of the inquiry into these systems pointed to the necessity to identify and design new solutions for (1) promoting the use of the online digital archive across the entire investigation process, (2) transforming the archaeological report from being a static and final text to a dynamic, open, and non-definitive description, and (3) identifying a platform capable of making as much as possible the data findable, accessible, interoperable, and reusable.

4.1.3 Design of Västra Vång and Gribshunden

Given these needs and the evident shortcomings of the dualistic and separate approach to data documentation and publication (3D web visualization for data publication and 3D GIS for data collection), it was clear that to achieve the desired goal, it was necessary to design an information system capable of combining — all in one — aspects of documentation, management, and publication (Katsianis, 2012).

The use of 3DHOP for managing the entire documentation was not ideal for achieving this goal, and current online 3D GIS solutions are not designed to host any dynamic forms of data reporting.

A more appropriate solution was identified during an internship experience at the French National Institute of Art History (Institut national d'histoire de l'art, INHA), where I had the opportunity to collaborate with and learn from experts in cultural heritage data modelling based at the Digital Research Service (Service numerique de la recherche, SNR). Their long-term expertise in cultural heritage documentary data structuring, managing, and publishing was invaluable for conceptualizing and designing a system capable of incorporating all the elements needed to advance the research.

Through such a collaboration, it was possible to find solutions for combining a structured database oriented towards the semantic web with the web-based 3D visualization platforms developed during my experiments (3DHOP). Specifically, the GIS database scheme developed in the previous field projects was remodelled employing a new data formalization based on a semantic approach. Finally, its entities and properties were identified, and determined according to standard ontologies.

This work was carried out using Omeka S, a powerful Content Management System (CMS) designed for institutions interested in connecting digital cultural heritage resources online. Omeka S facilitated the identification of a data management structure characterized by logical relations, through which it was possible to interlink all the records produced during the archaeological investigation.

Omeka S's modular structure was chosen because it allowed a smooth integration of 3DHOP, providing the ideal visualization and data management environment for further developing my experiments and exploring my questions.

Once created (2021), the new information system was first tested in the ongoing investigation activities carried out at the archaeological site of Västra Vång, Sweden. The site of Västra Vång is characterized by a unique set of digitally-generated data produced across multiple excavation campaigns. This research environment represented the perfect case study to test this new approach.

Designing and developing the system at INHA and completing and testing the validation with the data from Västra Vång allowed the identification and addressing of issues and flaws as soon as they appeared. The results of this experiment led to the creation of the first version of the Archaeological Interactive Report (AIR), a web platform designed to incorporate and archive the full set of archaeological records (including data from advanced 3D recording technology) and edit multiple narratives linked with the excavation archive. The positive results in the collection, management, and editorialization (Vitali Rosati, 2016) achieved in Västra Vång (*Paper IV*), encouraged the further development of the system for addressing other aspects of current archaeological field practice.

In further developing AIR, the aim was to test its functionalities within a case study that retains relevant differences in field investigation methods (maritime field investigation) for assessing the system's effectiveness in promoting knowledge generation within different — and more challenging — investigation environments. Moreover, it was necessary to evaluate the limitations and potential of the system in supporting archaeologists' daily documentation and as a tool for supporting field interpretation.

Various experiments were developed within the framework of the underwater excavation of the shipwreck of the Gribshunden, an ongoing research project started in 2019 through a collaboration between Lund University and Blekinge Museum. The aim, in this case, was to assess whether AIR could manage field investigation campaigns not strictly based on the single-context method and, most importantly, characterized by limited access to the materials. Gribshunden represented the perfect case for investigating these aspects and gaining a deeper understanding of the potential of using an open, interlinked 3D web archive to support complex archaeological interpretations. The results of the experiments carried out at Gribshunden highlighted the need to implement new tools for overcoming the system's limitations in supporting field investigations not based on the single-context excavation method. Moreover, the capacity of the system to grant access to materials inaccessible to most users *de facto* increased the quality of the interpretations (*Paper V*).

The occasion to evaluate AIR's ability to support archaeologists' daily documentation and field interpretation, came during the latest field investigation campaign in Västra Vång. During the 2021 campaign, the system was used as the primary tool for recording and visualising the excavation data using a complete 3D visualization environment. Before the excavation started, the excavation participants were instructed on how to use the system. This new digital approach to documentation had minimal implications for the site logistics (*Paper IV*).

With such positive results, the same experiment was run at Gribshunden (2022 field campaign) to critically evaluate the impact of real-time documentation in such a complex investigation environment. Following a short training session on how to use the system, the archaeologists working on the project began to use AIR to review the information recorded in the 3D web archive. As at Västra Vång, this approach allowed a broader picture of the information to be retrieved during the investigation with minimal impact on the site logistics (*Paper V*).

Other case studies not included in the publications were developed across the years for experimenting with minor — but still significant — aspects of my research (see section 5.1.5). Specifically, the work conducted in Vambåsa, in collaboration with Blekinge Museum, and the excavation at the archaeological site of Domsten, conducted in co-operation with Sydsvensk Arkeologi, were crucial experiences for understanding the capacity of 3D web visualization platforms to function as tools for supporting the construction of visual narratives for illustrating unconventional and complex investigation practices.

5. Parallel experimentation: details

5.1 Case studies and experiments

Four main sites were selected as case studies to conduct the experiments. The use of the same excavation method (single context) and recording techniques (3D documentation) made them suitable for this study. The overlap of the experiments over time and across sites promoted the constant cross-fertilization of the methods, techniques, and tools that were developed, tested, and evaluated during the experiments.

The experiments generated a massive volume of data that were systematically processed, transformed, and implemented into the systems developed to address the different questions formulated.

This section offers an overview of the methodologies developed for these purposes and clarifies the motivations that led to specific methodological decisions. The following paragraphs illustrate the work carried out in six distinct case studies during eleven investigation campaigns undertaken between 2018 and 2022. They also clarify how the data recorded over these years have been processed, structured, and published to identify new digital practices capable of strengthening the connection between archaeological reports and field archives and thereby enhance archaeological practice. The description follows the order in which the articles are presented in the dissertation.

This section also provides a presentation of the web platforms developed and tested during this doctoral project, describing their logical design and the technical choices made to shape them to meet the specific excavations requirements. Such work included testing new approaches and assessing the benefits and flaws of spatial technology and online visualization systems to support field investigation and knowledge production.

Throughout the project, collaboration with researchers from different institutions working on diverse aspects of archaeological practice was pursued. The opportunity to work with such a large group of specialists was invaluable in gaining new perspectives and considering them at all stages of the work. The participation in so many diverse field projects and the development of international collaborations provided a broad perspective concerning the role of digital technologies in supporting archaeological practice, generating new knowledge, and identifying flexible and dynamic practices designed to solve complex research questions.

5.1.1 Experiment 1: Kämpinge

The first experiment was carried out by reusing the data from the Mesolithic site of Kämpinge, a field course for masters' students aimed at identifying intact cultural layers. The aim of this experiment was to evaluate how effective web-based systems are in reusing 3D data from completed excavations for composing archaeological interactive reports. The data reused had been collected during four excavation seasons using the single-context method.

Kämpinge is a Mesolithic site located in the south-western end of Skåne, Sweden. The site is known for numerous prehistoric artefacts retrieved over the years, and it is part of a larger group of Middle and Late Mesolithic coastal sites in the Öresund region dating from 8500–6000 cal BP (Dell'Unto et al., 2017, pp. 633-634).

Between 2014 and 2017, archaeologists and masters' students from Lund University undertook several excavation campaigns to assess the presence of intact stratigraphic layers. The excavations were conducted over four campaigns. Beyond the digging activities and standard analogue documentation methodologies, the students learned to perform 3D documentation combining Image-Based 3D Modelling techniques (Remondino & El-Hakim, 2006) and Real Time Kinect GPS (see Figure 5). All the records were implemented into a geodatabase and visualised through a 3D Geographic Information System customized for supporting the fieldwork.

I reused the data produced during the four excavation campaigns to perform a preliminary assessment of the limitations and potential of 3D web data-management platforms in support of archaeological data reuse. With this experiment, I was interested in understanding to what extent new visualization platforms can be repurposed to enable new dynamic forms of archaeological reports.

During the excavation campaigns, a well-structured digital documentation methodology was used in Kämpinge for the 3D recording of the features encountered during the investigations (Dell'Unto et al., 2017). This enabled me to make successful reuse of the datasets generated by the investigation, even though I had not actively been involved in the field excavation.

After reviewing the whole dataset produced during the excavation (which included 87 3D models of archaeological contexts and features), I reprocessed the 3D data to produce a dataset characterized by consistent parameters, and I georeferenced and re-imported almost all the 3D models into a new geodatabase created using ArcGIS Pro. Once the entire dataset was harmonized, I used the Interactive Visualization System (IVS), based on 3DHOP, to share online a selection of 3D models recorded during the past campaigns. This platform included several interactive functions for dynamically generating different scenarios, retrieving measurements, and connecting the 3D scenes with different sets of data, mainly PDF files, pictures, and external links.

Figure 5. Kämpinge
Top left: students working in the field; top right: students performing analogue graphical documentation; bottom left: excavation activities; bottom right: digital documentation performed with the use of a tablet in the field. Photographs by Jan Apel.

The preliminary tests demonstrated the capacity of 3DHOP in delivering efficient and dynamic 3D interactive web visualizations of entire excavation sequences. However, although the platform proved to be very effective for publishing 3D datasets, it did not include any function for using the system for editing an archaeological report.

For this reason, the work carried out in Kämpinge focused on creating a dedicated set of tools for using the system as a primary means for editing a dynamic archaeological report. This experiment led to the creation of the Interactive Reporting System (IRS) (*Paper I*).

The possibility of linking external media within the platform was not an ideal solution. A better option was in fact exploiting the benefits of 3DHOP to empower 3D content exploration with more dynamic and interactive tools. The inspiration came when working with the predefined view and hotspot functions tested during the development of previous experiments. 3DHOP allows setting specific 3D scenes and retrieving information by interacting directly with parts of the 3D model. My collaboration involved the Visual Computing Laboratory, which is based at the Italian National Research Council (CNR-ISTI), and developed the original 3DHOP framework. This system was designed to host archaeological records excavated using single-context methods. For this reason, the archaeological context was kept as the "core element" of the visualization. In this way, it was possible to track, display, and describe — in the virtual space — the spatial relations among the different materials uncovered and recorded in the field.

Visualising and reporting a research activity developed across multiple seasons presented several challenges. For example, various trenches were completed in different seasons and excavated by variable groups of archaeologists.

The easy way of addressing this issue was to structure the records by season and then by trench. This solution matched the traditional structure currently used to construct archaeological reports. In addition, it facilitated the creation of an initial data structure designed for bridging 3D models and textual descriptions (see Figure 6). The identification of such a structure allowed the designing of a user-centred interface that facilitated the creation of interpretations and the writing of the reports.

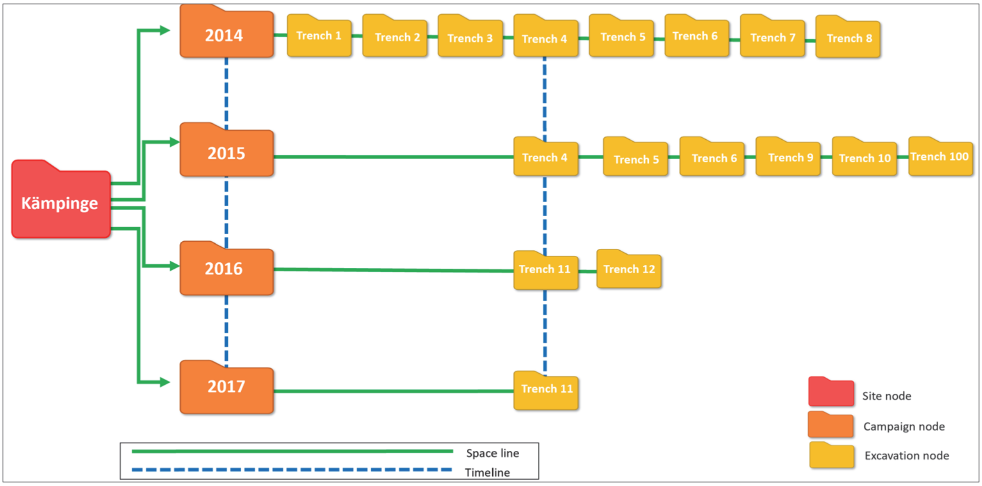


Figure 6. Database conceptual model
The diagram illustrates the conceptual model of the Interactive Reporting System (IRS), where the nodes allow space and time navigation across the excavation campaigns and trenches investigated at the site. Image by Paola Derudas.

The system is characterized by a modular structure that includes and combines interactive paragraphs formed of textual parts and 3D models. It was created in collaboration with the Italian National Research Council and involved feedback from multiple stakeholders. Specifically, the online platform was constructed using graphic storyboards employed to identify and visually define the behaviour of the diverse components (see some storyboard excerpts in Figure 7).

Once the skeleton of IRS was completed, it was possible to implement the platform using the information from the archaeological reports created during the previous campaigns (2014, 2015, and 2016).

The report was edited using the authoring version of the web page where, through the Scene Editor tab, all the 3D contents used to define the trench could be imported (see Figure 8b and 8c). I created as many report blocks as necessary to describe the archaeological features visible in the trenches. For each block, I built the corresponding 3D scenes by choosing the 3D models of the represented contexts, and I set the more appropriate point of view to support the text. Once I created all the blocks required for the report, I used the Text Editor box available in IRS to enter the text (see Figure 8e). Once I completed the report, I shared the platform with the project director, Professor Jan Apel, who directed the excavations at Kämpinge across the four campaigns. He reviewed the information entered in the IRS, and then, after a few training sessions, he was able to use the web platform to create new blocks, add or delete texts, and change the scene in the 3D canvas.

Although Jan Apel had already completed and submitted standard reports describing the activities carried out from 2014 to 2016, he tested the use of IRS for compiling the archaeological report of the field investigation carried out in 2017. This practice led to the identification of new components that were promptly incorporated into the digital report, such as a tool for creating orthographic views.

IRS was utilized with ease and, during the COVID-19 pandemic, when all field courses were cancelled, it was used at Stockholm University to familiarize students with archaeological field practice. The students were trained in using IRS, and by the end of the course, they were asked to use the platform to describe their interpretation. This experiment was very successful, and after the pandemic, even though the field course was restored, the platform was included in the teaching program and is still part of the course today.

Results

The IRS encouraged transparency and enabled data reuse and reinterpretation. Furthermore, thanks to its modular structure and dynamic functionalities, the system allowed a deep interaction with the 3D contents and the standard format documentation accessible through the report. Despite the system including only part of the information recorded during the investigation, this approach opened new research trajectories, and it proved the potential of incorporating 3D visualization technology for supporting new interpretations and developing dynamic narratives.

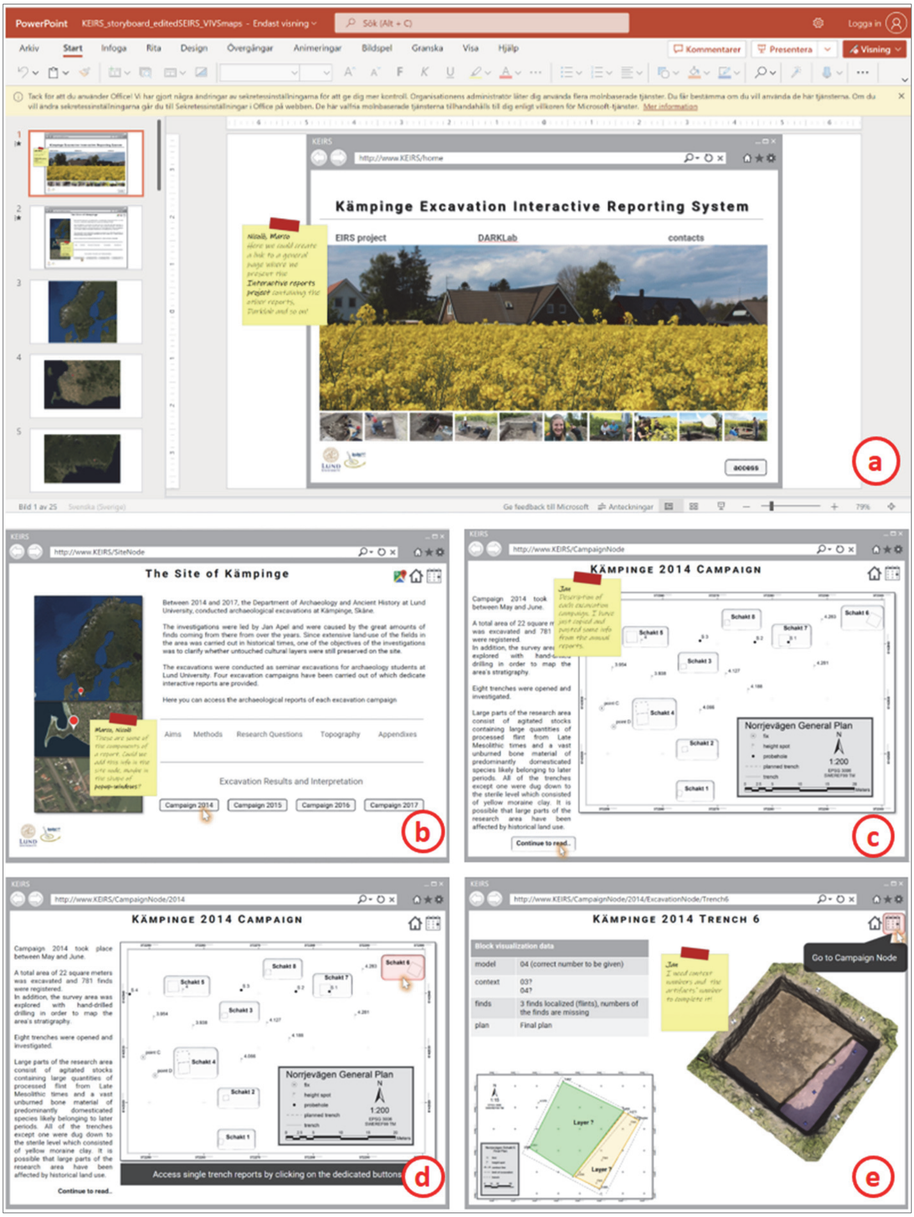


Figure 7. Storyboard

Screenshots from the storyboard used to conceive the structure of the Interactive Reporting System (IRS), which helped to design its behaviour and the interaction among all its components. The letters indicate the IRS components: homepage (a); site description and access to the field campaigns (b); visualization and access to the trenches in a field season (c, d); trench visualization (e). Image by Paola Derudas.

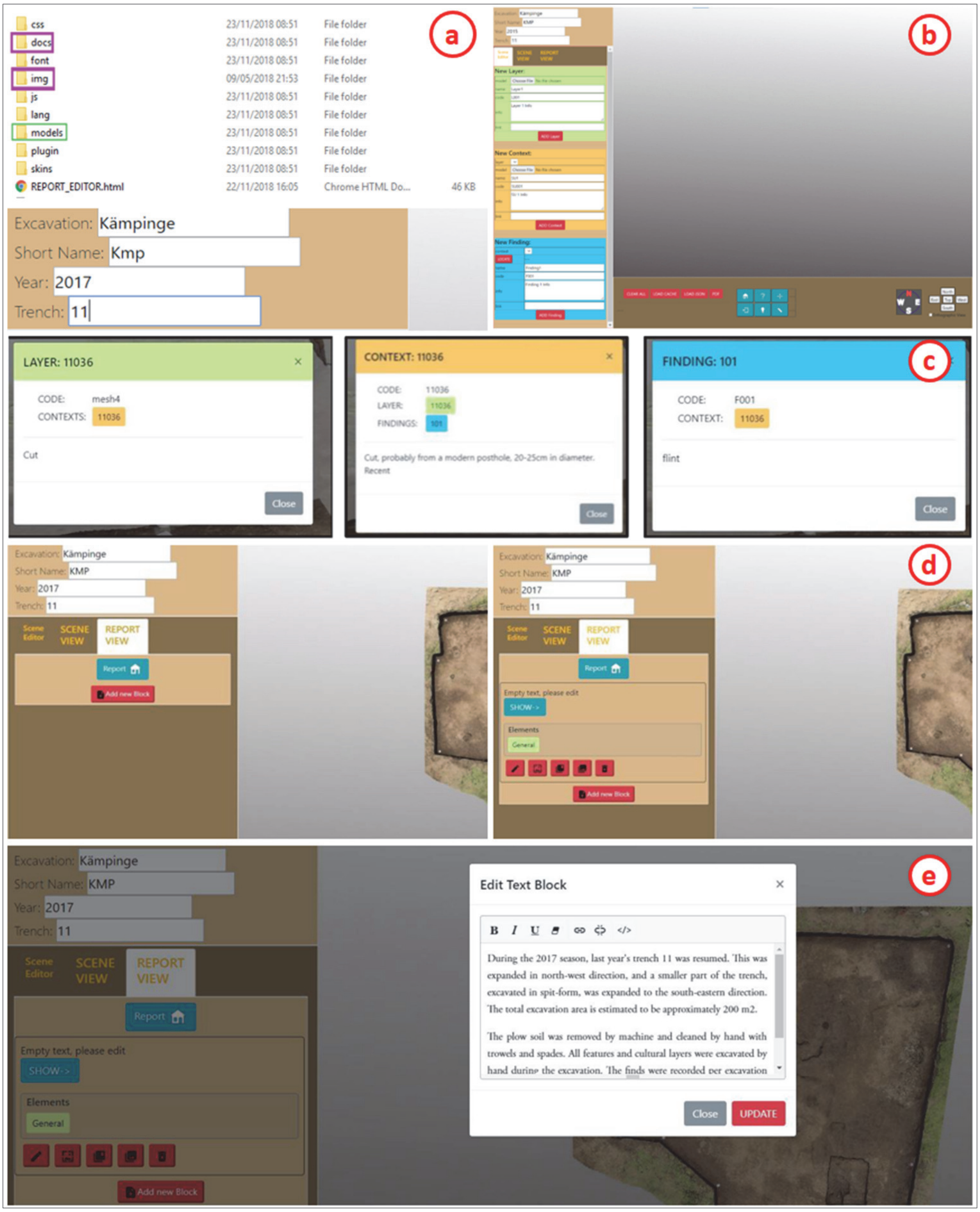


Figure 8. IRS implementation

Building the report through the Editor Application into the Interactive Reporting System (IRS): media folders and record block registration (a); 3D content implementation with the scene editor (b); connections among content are displayed (c); Report block construction by choosing components and setting the 3D scenes (d); writing the narrative part with the text editor (e). Image by Paola Derudas.

5.1.2 Experiment 2: Södra Sallerup

The second experiment was carried out at the prehistoric site of Södra Sallerup during a field course aimed at training undergraduate students in fieldwork activities. This experiment aimed to investigate how effective a 3D web-based visualization system is in supporting excavation data analysis and interpretation and contributing to a deep-learning approach to field education. The investigations were conducted using the single-context method, with the students excavating multiple excavation units of Bronze and Iron Age layers.

Södra Sallerup is a multi-period archaeological site primarily noted for the presence of Neolithic flint mines. It is located in southern Sweden, east of Malmö (Skåne). The excavation area is 15 x 11 metres in extent, and this part of the site is dated to the Bronze and Iron Ages (Berggren, forthcoming). Such an area offered a variety of artefacts such as pottery sherds, animal bone fragments, and reused or redeposited Neolithic flints.

The students excavated the layers within a one-metre-squared surface grid, with 10 cm spits used for subdivision in the case of thicker layers (see Figure 9). For many students, this was their first excavation experience, and for this reason, the main objective of the field course was to be introduced to the archaeological investigation activities based on the single-context method (excavation, documentation, data management, and interpretation). Concerning the documentation aspects, the aim was to provide the students with an overarching presentation of all the techniques and tools currently used in archaeological practice, including 3D advanced recording methods.The previous experiments in Kämpinge focused on data reuse and did not include an assessment of the limitations and potential of using 3D web platforms to support fieldwork. At this stage of the research, it was necessary to gain information on how the use of such systems in the field would affect archaeological practice and to obtain practical feedback to improve system design. For this reason, the main objective of this experiment was to observe further the effects of 3D web visualization systems in supporting ongoing field investigation. Moreover, considering the impact that such systems had during field courses, the capacity of 3D web platforms to facilitate field education practice could be further assessed.

The experiment was developed across two excavation seasons, corresponding to two field courses. The acquisition strategy designed to support the fieldwork was carefully planned and was introduced to the students well ahead of the beginning of the excavations.

The Södra Sallerup IVS was better suited for this experiment. The system was in fact originally designed to publish and explore the archaeological features from field investigations, and to provide the students with the tools for reviewing the contexts and excavation units previously implemented in the system. The platform adopted for this experiment was similar to the one previously tested in Västra Vång, with the difference that in Västra Vång, the system was customized to provide specialists working off-site access to a detailed visual representation of the excavation sequence, and it was not intended to be used by archaeologists working on-site.

The first excavation campaign, in 2019, mainly focused on recording the archaeological contexts and features encountered during the field investigations, and it was dedicated to identifying practices for producing 3D records customized for an optimal visualization on the web.

Figure 9. Excavation at Södra Sallerup in 2019
A snapshot of the excavation activities at Södra Sallerup: students working in pairs in their excavation unit. Photograph by Paola Derudas.

The team was composed of 22 students that employed IBM techniques and a total station to produce the documentation and experiment with new 3D acquisition methodologies.

During the post-excavation activities the students processed the information acquired in the field, and after a short training process, they used the Interactive Visualization System to support the writing of the traditional report.

In 2020, during the second field investigation campaign, despite the reduced number of participants due to the COVID-19 pandemic, the students used the IVS developed in 2019 directly in the field to review the sequence of contexts detected and excavated during the previous excavation (see Figure 10). Differently from the previous year, when the site had not yet been investigated, they could rely on their colleagues' documentation and a much more detailed visual description of the site (see Figure 11). The 3D web platform was, in fact, available in the field to review the investigation process undertaken during the previous season. This represented a significant advantage in their practice.

Figure 10. Excavation at Södra Sallerup in 2020
Students excavating at the site of Södra Sallerup. Due to the COVID-19 pandemic, students worked individually in the excavation units. Photograph by Paola Derudas.

Results

The results obtained at Södra Sallerup highlighted the potential of 3D web platforms in supporting the field investigation process. In particular, the experiment demonstrated how the availability of detailed 3D documentation from previous investigations encouraged field interpretation and provided significant support during the entire process, including field interpretation and report writing. The experiment also demonstrated the impact that 3D web visualization platforms have on higher education and specifically their capacity for supporting students during archaeological field practice.

Despite the positive results, this work revealed several significant limitations. The impossibility of implementing the data in the field prevented the excavation team from reviewing the work carried out during the investigation and performing a reflexive approach. The data management system at the core of IRS and IVS was not, in fact, ideal for managing a more extensive and diversified set of data.

The lack of a structured data archive at the core of the 3D web visualization system precluded the generation of more advanced visual simulations, preventing an efficient and dynamic connection between the archaeological report and the data. These aspects were addressed within the framework activities of the Västra Vång and Gribshunden projects, where I had the opportunity to implement new experiments to progress my research.

Figure 11. IVS implementation in the field
Implementation of the Interactive Visualization System (IVS) in 2020 during fieldwork, to allow the students to use it at the beginning of the post-excavation work. Photograph by Åsa Berggren.

5.1.3 Experiment 3: Västra Vång

The third experiment was conducted at the Iron Age site of Västra Vång. The excavations aimed to better comprehend the hill-site's stratigraphy and were conducted across several campaigns applying the single-context method. The aim of this experiment was to evaluate the effectiveness of an information system for the documentation, management, and publication of data and reports from single-context-method excavations.

Västra Vång, an Iron Age central place in the region of Blekinge (south-eastern Sweden), was identified in 2004 when archaeologists recognized clear evidence of occupation spanning from the Roman Iron Age to the Viking period (0–1100 CE) (Henriksson, 2006, 2022a). The central role of Västra Vång and economic prosperity throughout the Scandinavian Iron Age are proven by the rich find materials retrieved during the numerous excavation campaigns conducted at the site. In the central part of the site a ritual complex was identified that was likely inhabited between the Scandinavian Late Bronze Age (1100 BCE–500 CE) or the Pre-Roman Iron Age (500 BCE–0 CE) (Henriksson, 2016), and the Late Germanic Iron Age (Swedish Vendel Period 550–800 CE) (Svensson & Derudas, forthcoming).

I joined the Västra Vång field investigation in 2017 (see Figure 12). Over the course of my doctoral research (2018–2023), I was able to design several experiments. Differently from the previously described case studies, a team of experienced archaeologists and specialists carried out the investigation at Västra Vång.

Three of the four excavation campaigns focused on clarifying the hill-site's complex stratigraphy (2017, 2019, 2021), whereas the 2018 campaign investigated portions of the surrounding settlement. Besides participating in the excavation activities, I performed most of the digital documentation produced during the investigations using spatial technology, 3D visualization, and publishing online the entire investigation sequences identified across the years through 3DHOP.

The 2017 field campaign

In the 2017 campaign, a successful workflow for 3D data recording was defined. The same approach was carried out across all excavation seasons in Västra Vång. All information recorded in the system was imported in a geodatabase model previously realised within the framework activities of the Kämpinge project (Dell'Unto et al., 2017), and continual work was carried out to establish a data model suitable for the registration of the archaeological evidence uncovered during the investigation. The geodatabase was also customized to meet Swedish contract archaeology standards and the records were visualised using ESRI ArcGIS Pro (see Figure 13).

Unlike using a ready-made database, we designed and built an excavation relational database structure that perfectly served our needs and that was crucial for constructing the latest system that was employed during the 2021 investigation campaign. In 2017, I used 3DHOP for the online 3D publication of the sequence of contexts and features identified during the excavations.

Figure 12. Västra Vång

Top left: the site of Västra Vång (drone photograph by L. Persson); top right: the hill at the centre of the site complex (drone photograph by L. Persson); bottom left: gold artefacts from the hill-site (photograph by P. Derudas); bottom right: archaeologists who participated in the 2017 excavation. Photographs by Blekinge Museum.

The Interactive Visualization System initially implemented at Västra Vång was similar to the one used later on at Södra Sallerup, with the difference that the 3D models at Västra Vång were made available for testing the efficiency of the 3D web visualization platform in granting remote access to different stakeholders during the ongoing excavation activities.

For example, specialists working on chemical and thermoluminescence analysis of geological samples could review the stratigraphic sequence of contexts where the materials had been retrieved without leaving their facilities. Moreover, the web platform was often used during the project meetings for discussing results, reviewing stratigraphic relations, and planning future investigations. During this campaign, I produced 30 textured georeferenced models representing the trenches, the contexts, and the relevant artefacts when still *in situ* (see Figure 14).

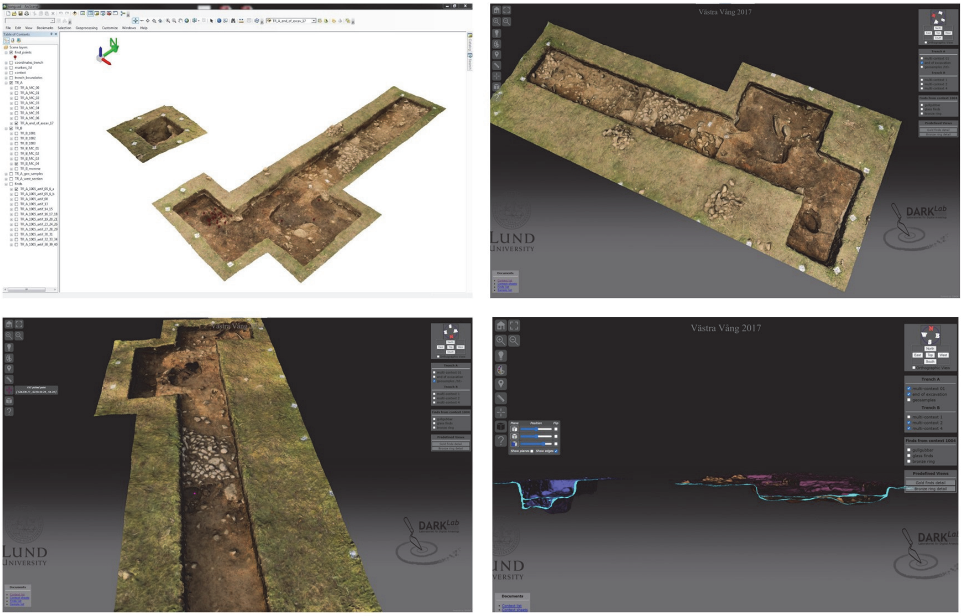


Figure 13. IVS at Västra Vång
Top left: 3D models of the trenches imported into the 3D GIS; top right: 3D model of Trench A visualised in the Interactive Visualisation System (IVS); bottom left: picking co-ordinate information from the 3D model documenting the geological samples taken in the IVS; bottom right: combining multiple meshes and sectioning them in the IVS to measure the soil removed during the excavation activities. Images by Paola Derudas.

Figure 14. Artefacts *in situ*
Left: two gold artefacts 3D recorded *in situ* during the 2017 campaign (see also Figure 12, bottom left) are visualised in the IVS using the 3DHOP ability to create predefined views in specific parts of the 3D models; right: detail. Images by Paola Derudas.

Once the field investigation was concluded, a selection of 3D models was published through the web platform to present the stratigraphic sequence and summarize the results. This experiment was developed very early in my doctoral studies, and the web platform did not include tools for editing a report. These aspects were investigated later at Södra Sallerup and subsequently at Kämpinge.

However, the information retrieved during this campaign underlined the potential of WebGL to transform the field investigation from a close and isolated research environment to what Zubrow defined as a global and open digital village (Zubrow, 2006, p. 10). Furthermore, the results of this first experiment underlined the capacity of these systems to promote research across different dimensions (the digital and the physical) underlying the impact that 3D web visualization has on the discipline's organizational structure (Edgeworth, 2014).

The 2019 field campaign

In 2019, the trenches excavated in 2017 and 2018 were extended into the surrounding area that was not included in the previous experiment. The trenches were extended in order to understand the stratigraphic relationship of the contexts and features encountered during previous campaigns.

The digital documentation strategy was developed following the one employed in previous field campaigns; I used the 3D web platform for publishing the results after the excavation activities had finished. I recorded over 30 3D models, 12 representing the archaeological contexts and 20 representing the artefacts when still on-site.

During this campaign, the focus was on gaining a deeper understanding of the relationship between the 3D models visualised through the web and the database structure developed on-site (e.g., metadata). Specifically, the geodatabase used in the previous campaigns was further developed, and *ad hoc* custom domains (vocabularies) were added for preparing the system to host and connect the different types of 3D models registered during the investigation with the rest of the documentation (see Figure 15).

The identification of these aspects was crucial for (1) conceptualizing a platform capable of managing and publishing entire archaeological datasets collected in the field, and (2) establishing a dynamic relation between the entire excavation database and the report. Moreover, during this campaign I tested the implementation of new functions for further increasing the interaction with the 3D scenes. Specifically, a new template was developed for (1) dynamically generating 3D scenes by combining multiple models, (2) creating specific "static" 3D views to portray specific interpretations, and (3) modifying light conditions and visualization elements in the scene, with lights and sectioning tool (see Figure 16).

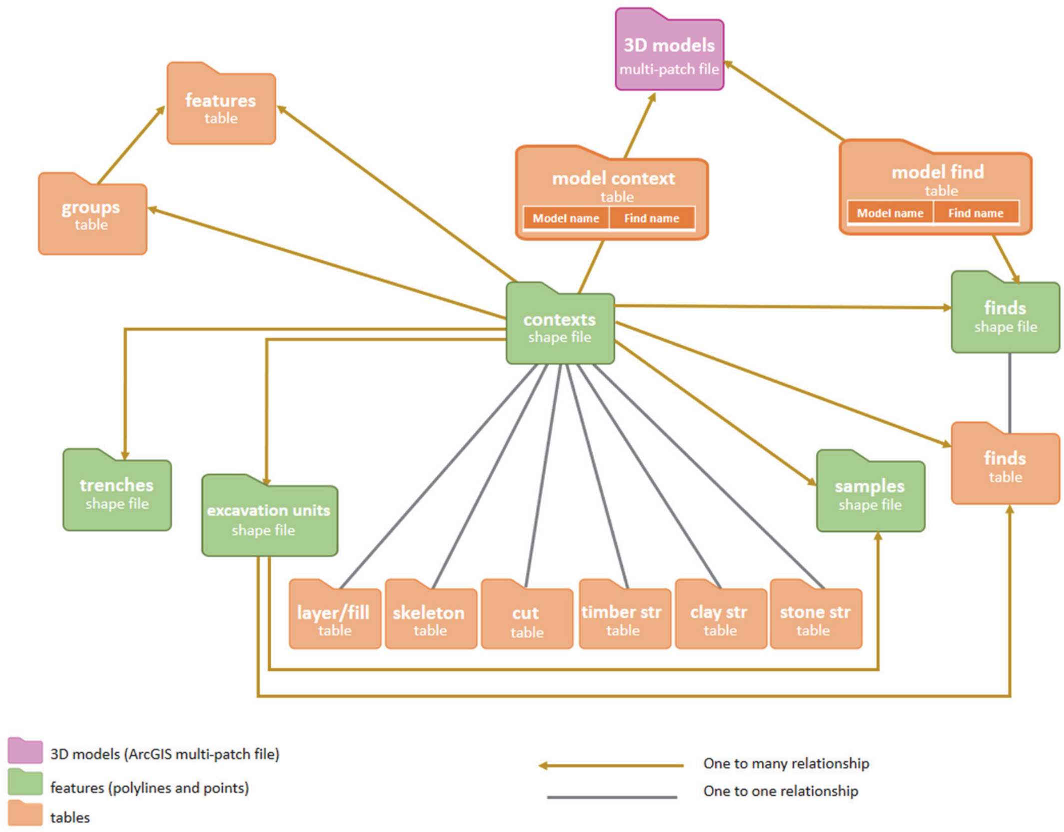


Figure 15. Database conceptual model
The conceptual model of the relational database embedded within the ESRI ArcGIS Pro database management system and the relationships among the elements constituting it: 3D models (multi-patch file within ArcGIS), features (polylines and points), and tables. Image by Paola Derudas.

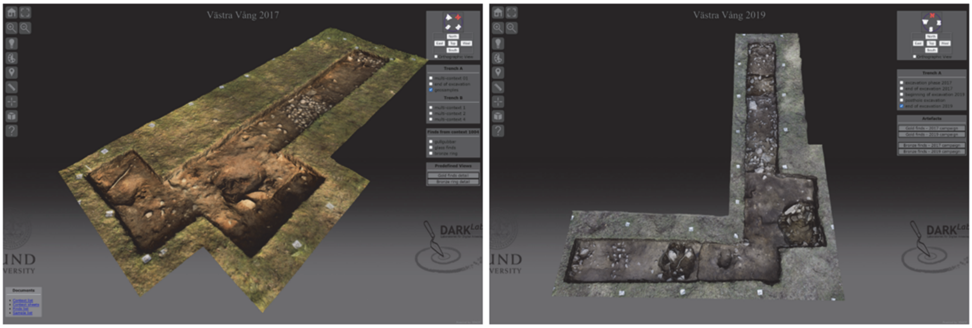


Figure 16. IVS tools
Constant elements characterize the Interactive Visualization System layout: 3DHOP tools on the left; heading and navigation at top right; 3D model views, visibility layers, and predefined views on the right. Images by Paola Derudas.

The 2021 field campaign

The 2021 excavation campaign expanded and investigated further the trench opened in 2019 on top of the hill. The excavation represented the perfect occasion for testing the Archaeological Interactive Report (AIR) and assessing the system's potential in supporting the archaeologists' daily documentation.

Before the excavation started, I implemented the complete archaeological documentation produced during the previous investigation campaigns, including the reports, into the newly developed AIR. After the system's successful implementation and validation, the data was used to write the archaeological report of the 2019 investigation campaign, finally establishing a direct link between records and text. Thanks to the capacity of AIR to keep the argumentation connected with the archaeological archive (Dallas, 2015), the archaeologists could read the report and interact with the excavation data in the same virtual space.

The previous experiments conducted in Södra Sallerup highlighted the advantages of using a fully implemented system capable of providing the archaeologists with a broad temporal perspective of the investigation, and Västra Vång represented the most suitable case study to assess these aspects.

During the one-week excavation campaign the south-east corner of the trench was reopened, extending the investigation area. Despite the small area, the field investigation turned out to be complex. The possibility of using AIR for recording and publishing in real-time a high-resolution 3D spatial documentation of contexts and artefacts retrieved on site represented a major opportunity for tracking the investigation process (see Figure 17).

Figure 17. Västra Vång 2021
Archaeologists discussing fragile artefact removal and documentation strategies. Photograph by Jens Larsson.

Furthermore, the possibility to share, revise, and discuss the archaeological evidence retrieved during the investigation in spatial relation with the archaeological records from previous campaigns encouraged numerous discussions and supported the formulation of new hypotheses.

A total of 14 3D models representing multi- and single-context areas and artefacts were recorded *in situ* during the excavation. Once ready, the archaeologists implemented the 3D records and the metadata available through the interactive context sheets embedded into AIR (see Figure 18).

Through AIR, the documentation including 3D models, contexts, and artefacts, was published online and made available live to all project participants and colleagues not on-site.

Figure 18. AIR at Västra Vång
Left: photographic acquisition for the production of 3D models using Image-Based 3D Modelling techniques; top and bottom right: using AIR in real-time — 3D data exploration at the site during fieldwork. Photographs by Jens Larsson.

The system automatically indexed the records and allowed a dynamic regrouping of the objects stored in the archive. These functions provided the users with flexible and dynamic access to the archaeological records. Moreover, thanks to the REST API available through Omeka S, data could be exposed in interoperable formats (such as JSON-LD), through basic semantic classes and properties and ready to be linked with other databases, according to a proper alignment of data model (*Paper IV*).

Results

The multi-year project at Västra Vång represented the ideal case study for the development of experiments that led to the creation of the IVS and, later, the IRS. The various experiments conducted across the years allowed the overcoming of the limitations of these platforms and the identifying of the characteristics of a new and more advanced system, AIR.

AIR allowed the management of the entire dataset of information collected during the field investigation and the generation of archaeological reports. AIR functioned as the primary tool for exploring and reusing the data and its media stored in the online archive. Using AIR enabled the dynamic and multimedia-rich archive to be interwoven with the scientific argumentation, thereby proposing a satisfactory solution for data accessibility, fragmentation, and reuse. Furthermore, its web semantic format allowed us to structure the data aligning it with the ontologies widely used in the cultural heritage field in order to comply with the FAIR guiding principles.

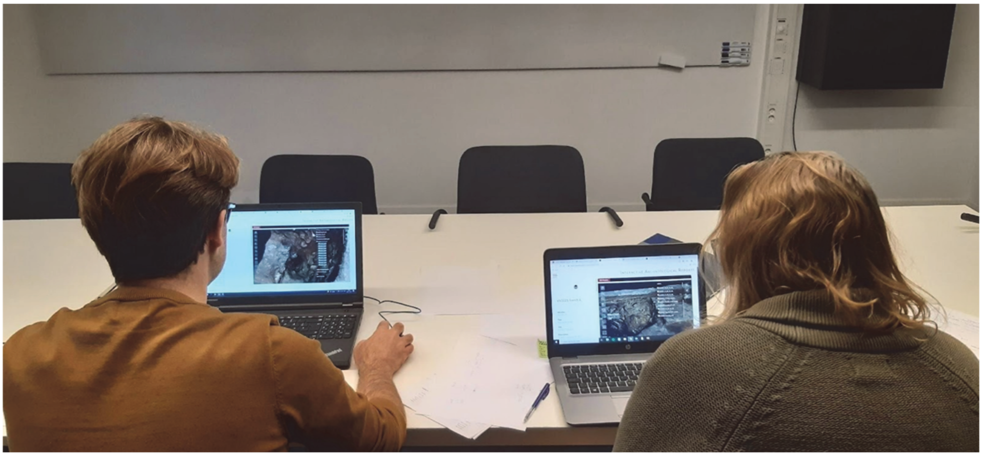


Figure 19. Post-excavation work using AIR
Using AIR during post-excavation work for reviewing the dataset and supporting data interpretation. Photograph by Paola Derudas.

5.1.4 Experiment 4: Gribshunden

The late medieval site of the Gribshunden shipwreck was the subject of the fifth experiment. The underwater excavations aimed to investigate the ship's role in late medieval northern European society. Several trenches were excavated over several seasons using a venture dredge. This experiment aimed to determine the effectiveness of an information system initially designed for terrestrial single context-based excavations as a tool for documenting, managing, and publishing data and reports of maritime excavations.

Gribshunden was the flagship of the king of Denmark and Norway, Hans, who sailed with it around the Baltic Sea and northern Europe from 1485. It was one of the first ships to carry artillery, and according to written sources, the ship sank after an on-board explosion in 1495 in the south-eastern Swedish archipelago of Blekinge. When the vessel sank, King Hans was sailing to Kalmar, in Sweden, for a political summit, where he expected to be crowned head of the Nordic countries. A local diving club identified Gribshunden in 1970s, but the first minor archaeological investigations only commenced in the 2000s 'and culminated with the recovery of the timber figurehead in 2015' (Adams & Rönnby, 2022; Eriksson, 2020).

Systematic investigations at the wreck began in 2019 when Blekinge Museum and Lund University started a research collaboration aimed at gaining a more accurate insight into King Hans's life and the ship's political impact. From the start, the research has been structured as a multidisciplinary endeavour involving specialists from many disciplines.

Digital archaeology plays a crucial role in the project, as it contributes to collecting and managing data on which the ship-structure reconstruction hypotheses can be based (see Figure 20).

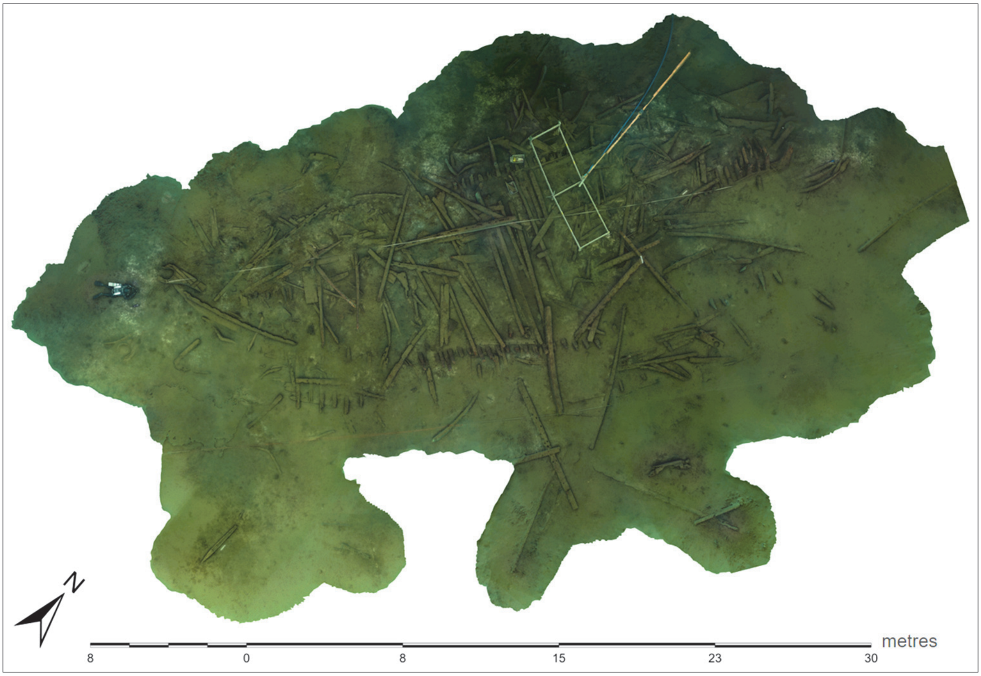


Figure 20. The Gribshunden shipwreck
Orthoimage of Gribshunden obtained from the 3D model. Image by Paola Derudas.

Besides the scientific objectives, Blekinge Museum and Ronneby municipality also co-ordinate public outreach and information dissemination aspects. This project provided the perfect environment for developing new experiments and testing various visualization strategies.

The research questions I addressed within the Gribshunden field investigation assess the capacity of 3D web visualization platforms to support field investigation practices characterized by minimal access to the materials. I was also interested in developing a data management plan to facilitate the connection between the archive and the report, encouraging the formulation of new hypotheses and interpretations within the time frame of the excavation fieldwork.

Since 2019, I have participated in the investigation campaigns developed by Blekinge Museum and Lund University. During the field investigation, I 3D processed, archived, and published online materials and contexts retrieved by the underwater archaeologists during the investigation. As opposed to the experiment carried out at Västra Vång, where the materials retrieved during the excavation were always available for closer examination, at Gribshunden, most of the archaeological features were accessible only virtually through the 3D online archive (see Figure 21).

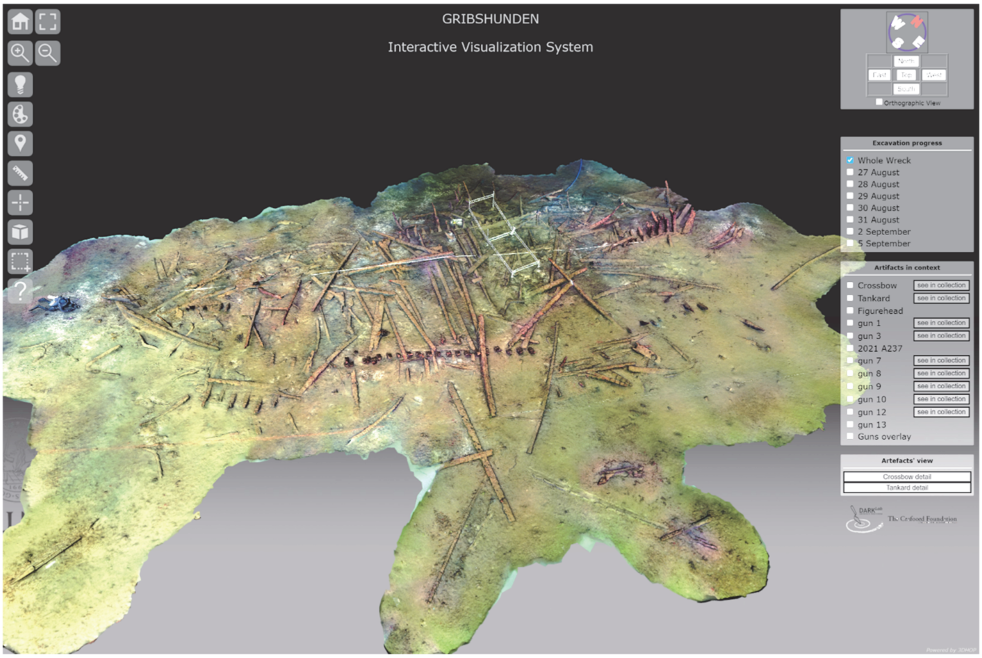


Figure 21. IVS at Gribshunden
The IVS represents the 3D online archive accessible to all research participants for virtually reviewing the excavation's materials and progress. Image by Paola Derudas.

Within maritime excavations, access to the site is constrained due to the investigation environment; therefore having the possibility to explore it virtually represents a major advancement.

Finally, I intended to investigate whether AIR, designed for terrestrial archaeological investigation based on the single-context method, could be satisfactorily employed to manage and publish archaeological records retrieved within the investigation activities of maritime archaeology in the context of post-excavation research.

The 2019 field campaign

During the 2019 field campaign, underwater archaeologists opened a trench to assess the depth of the archaeological deposits and to gain information on the ship's original structure. A professional photographer performed underwater photogrammetric acquisition to produce 3D models via IBM (see Figure 22). Further photogrammetric acquisitions were carried out using a 3D-printed hemispheric rig equipped with GoPro cameras (Pacheco-Ruiz et al., 2018); records produced using these techniques were processed and implemented in the Interactive Visualization System and later in the Archaeological Interactive Report.

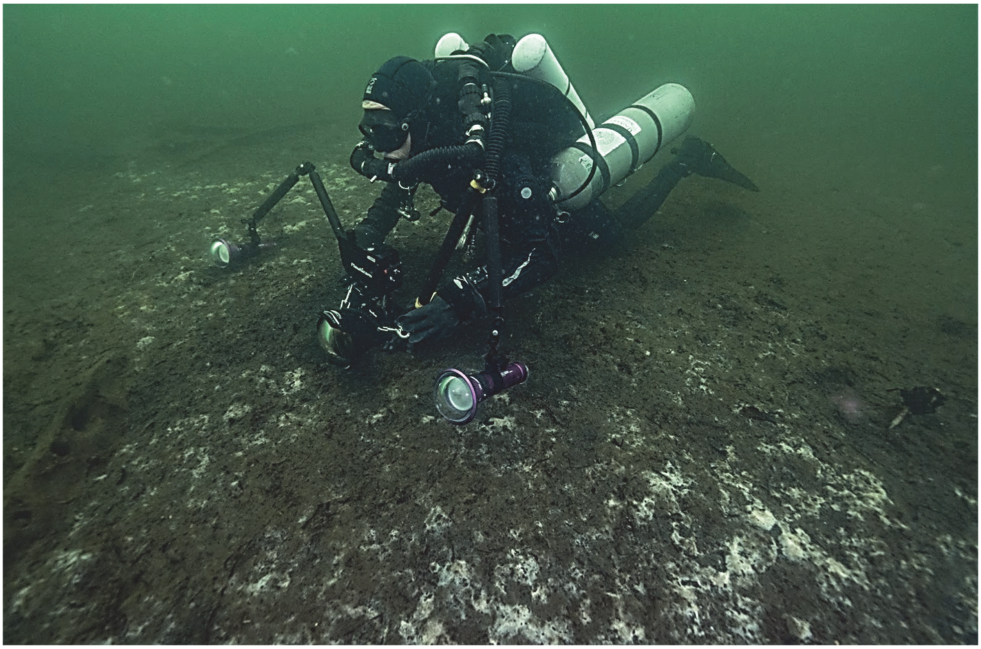


Figure 22. Underwater photogrammetry at Gribshunden
Underwater photogrammetric acquisition for the production of 3D models through Image-Based 3D Modelling techniques. Photograph by Brett Seymour.

A total of 9,546 pictures were used for producing a 3D model of the whole ship and seven diachronic models of the trench at different stages of the investigation. Working underwater prevented the use of ground control points; for this reason, I georeferenced the model of the wreck using a high-resolution multibeam sonar dataset produced before the start of the investigation campaign (Nawaf et al., 2021).

The 3D models created for visualising the different steps of the investigation were initially used to generate temporal bi-dimensional maps for annotating the features identified during the excavation (see Figure 23) (Rönnby, 2021). Before implementing AIR at Gribshunden, I had used the IVS to assess the capacity of 3DHOP to optimally visualise 3D content from such a large area as the wreck and the smaller excavation trench. On this occasion, the system also proved to be an effective choice, in that it enabled archaeologists to interact with all the visible features spread across the investigation area. The low visibility of the Baltic Sea prevented the divers from gaining sufficient visibility to explore the whole wreck at a glimpse. For this reason, the system was paramount for planning research and formulating new interpretations.

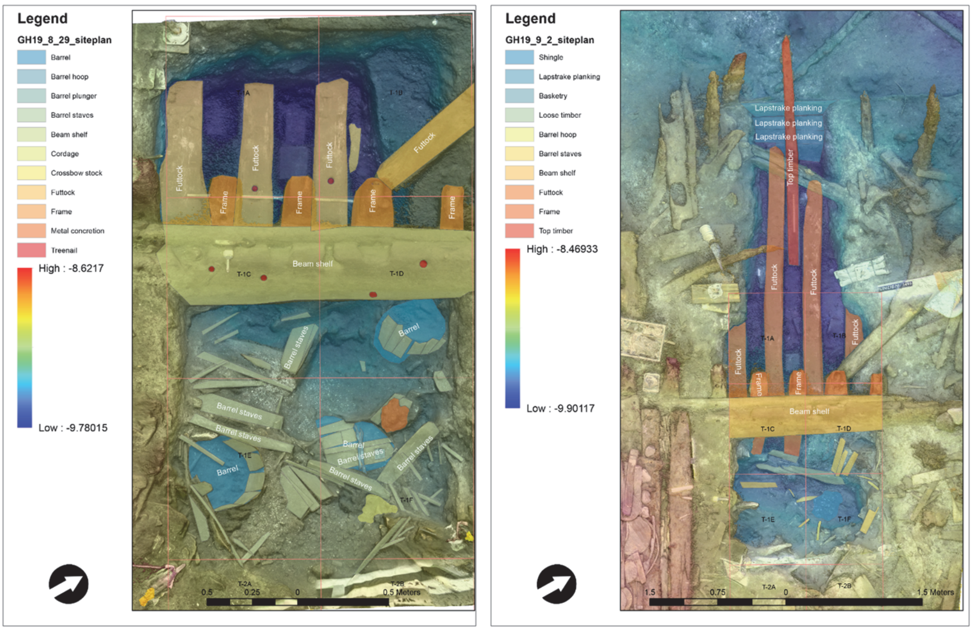


Figure 23. Bi-dimensional maps

Bi-dimensional maps produced after the end of the excavation campaign using orthoimages obtained from the 3D models and attached to the final (traditional) report (Rönnby, 2021). Images by R.Pacheco Ruiz.

I was interested in assessing the capacity of the IVS to dynamically simulate the spatial relation between the 3D models acquired underwater with the 3D artefacts collected and 3D scanned in the laboratory. Despite being visible in the 3D trenches, the artefacts were characterized by a low resolution and were very difficult to perceive. For this reason, I used IVS to superimpose the 3D high-resolution version of the artefacts acquired using a structured-light scanner in the laboratory with the photogrammetric 3D models of the trench containing the artefacts when still *in situ* (see Figure 24).

This approach was designed to promote data reuse by encouraging researchers interested in single artefacts to access and further explore information spatially related to those specific records.

Within the frame of this experiment, I also tested the use of tools for supporting archaeologists interested in further investigating the ship structure. The function allowed the generation of sections of different vessel parts, providing insights into the structural characteristics of the ship. Implementing this tool during the field investigation promoted discussion and encouraged the formulation of various hypotheses. This proved, once again, how implementing these tools in support of field interpretation impacts practice and encourages reuse.

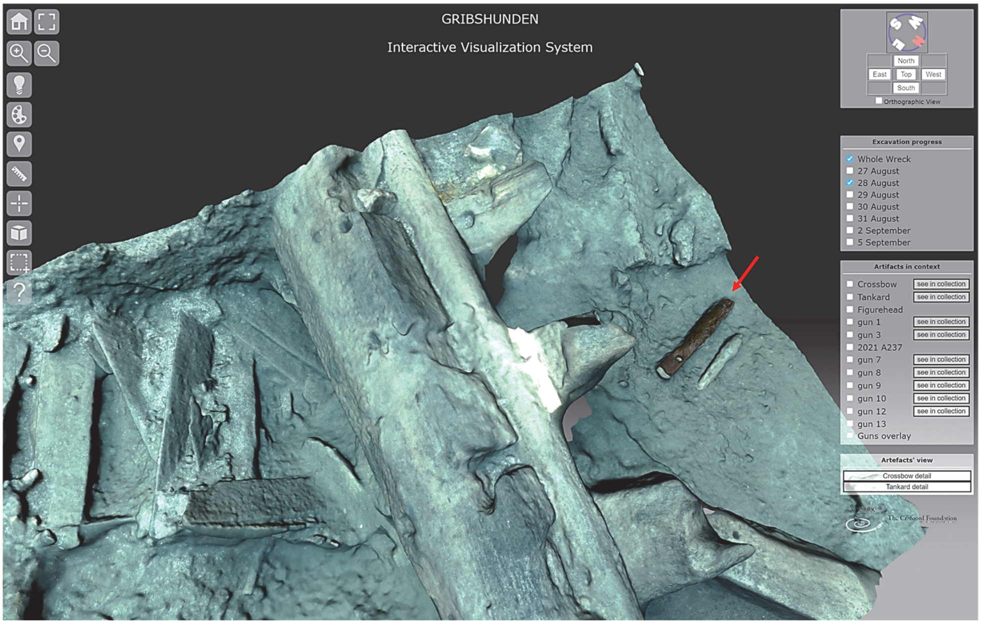


Figure 24. Finds in the IVS
The 3D model of a crossbow fragment (indicated by the red arrow), scanned with a structured light scanner before conservation, was repositioned in its find-spot in the IVS (indicated by the red arrow). Image by Paola Derudas.

The 2021 field campaign

After a short field campaign in 2020 to assess the presence of preserved large artefacts surrounding the shipwreck, a more extended field investigation was carried out in 2021. The goal of the 2021 excavation was to further investigate the areas surveyed during the previous seasons and document and recover a few detected artefacts. As in the previous campaigns, underwater photogrammetry was employed for producing the 3D documentation. Once generated, the 3D records were georeferenced using the virtual model of the whole shipwreck produced in 2019. Once available, I imported the 3D models in the IVS, merging the results of this campaign with the records available from the previous campaign, including 3D models of the gun carriages recovered in 2002 and more recently acquired with structured light scanners at the Blekinge Museum (see Figure 25). The scanned 3D models and previous photogrammetric surveys were accurately integrated via appropriate scaling and georeferencing.

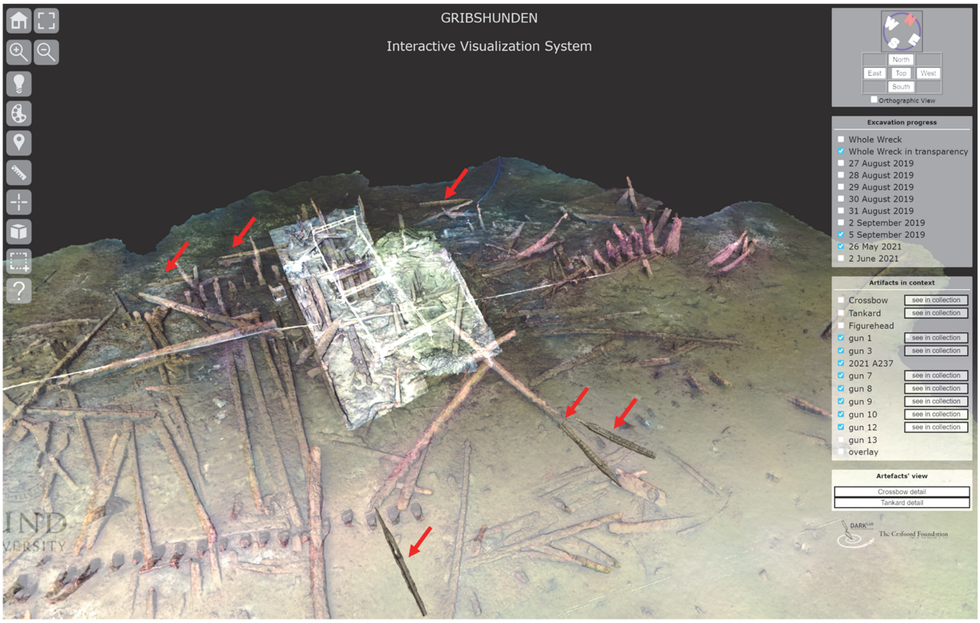


Figure 25. IVS campaign 2021
Excerpt from the 2021 version of the IVS: on a transparent model of the whole wreck the models of the 2019 and 2021 campaigns are made visible, and the gun carriages scanned at Blekinge Museum are replaced in their fid-spot. Image by Paola Derudas.

This final implementation undoubtedly proved the many positive aspects of employing 3D online visualization, and specifically the IVS, for supporting field investigation practice in such complex environments. The tools available through the system encouraged archaeologists and specialists to broaden their perspectives and gain a holistic overview of all the scattered information retrieved across the various investigations. However, the lack of a robust data management system for structuring and dynamically connecting the records produced during the investigation prevented complete access to the full set of data available in the archive. For this reason, I started testing AIR with data from the Gribshunden project.

After successfully using the system with the Västra Vång datasets, I wanted to assess whether its data structure — designed for supporting terrestrial archaeology — could also be employed in maritime excavations. The system allowed a better engagement with the dataset collected during the various investigations, granting access to all the records available in the archive, and furthermore, to connect semantics to geometry (Drap et al., 2013). The most challenging aspect was the reproduction — in a 3D environment — of multi-temporal representations of the elements retrieved within the same deposit; a similar representation has been previously performed in a bi-dimensional environment using orthoimages (see Figure 23).

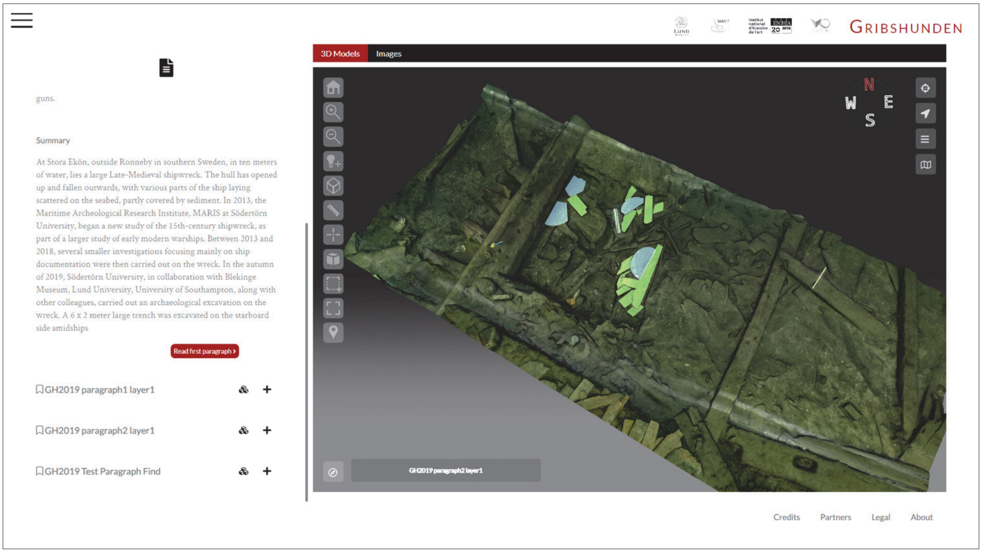


Figure 26. 3D annotation within AIR
3D annotation of the ship elements and visible artefacts as contexts to record their information into AIR. This solution, even if graphically appreciable, did not allow appropriate documentation of the items. Image by Paola Derudas.

Being designed to support a single-context recording method, AIR was not ideal for this task. For this reason, a graphic 3D annotation tool was implemented in the system. The possibility of "drawing" 3D models directly on the 3D scene allowed for highlighting (and temporally organizing) specific elements visible on a large scene (see Figure 26). The implementation of such a tool allowed this issue to be overcome, extending the use of AIR to a broader set of field investigation environments. At the end of the 2021 excavation season, AIR was tested to write an interactive copy of the archaeological report of the 2019 excavation campaign (see Figure 27).

AIR proved to be efficient, and the successful results encouraged the research team to adopt this system as the primary data management tool for supporting future investigation campaigns. Furthermore, this choice provided me with the opportunity to develop my research further and define the final experiments for my doctoral research.

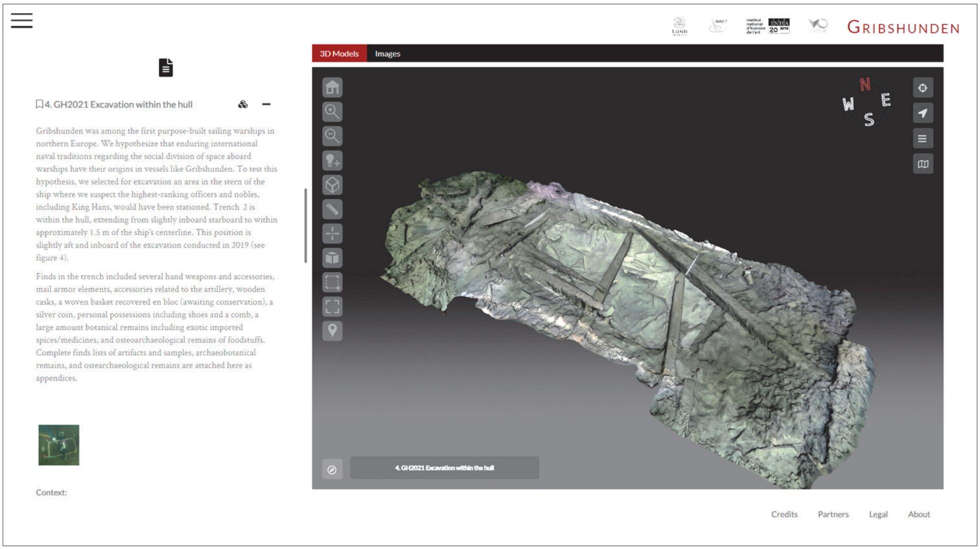


Figure 27. 2021 report using AIR
Screenshot of one of the paragraphs of the dynamic version of the 2021 report: on the left side, the textual description and the dynamic elements composing it, a context and its related artefacts, clickable and explorable independently in the 3D canvas, which is shown at right. Image by Paola Derudas.

The 2022 field campaign

The objectives of the 2022 campaign were to 3D document some key elements *in situ* considered relevant for reconstructing the ship's structure and extracting, archiving, and analysing environmental data from the recovered materials. To achieve such goals, two new trenches were investigated. As for the previous campaigns, underwater photogrammetry was used to perform the 3D graphic documentation of the archaeological features retrieved during the investigation and for documenting the excavation during different stages (see Figure 28). I worked with the data stream, processed the 3D data, and registered the finds into AIR. Even though the artefacts recovered during this campaign were fewer compared to 2021, I kept the same data management approach, registering them daily and enriching the record with photographs, this time directly into AIR.

Before the end of the excavation, all the data were archived and made available online to the team through AIR. Although the system was widely employed by the archaeologists working on site, I noticed that the excavation logistics did not include time for the archaeologists to engage with the digital archive.

Figure 28. Finds management
Top: the tiller being lifted to be 3D scanned ashore; bottom left: onshore 3D scanning of a wooden gun carriage before conservation; bottom right: 'the author undertaking finds implementation into AIR. Photographs by Brett Seymour.

I addressed this issue by creating a set of video tutorials for introducing AIR and its functionalities, and I shared the material with my colleagues. Together with the project director, the staff was asked to review the video material before the investigation started. During the field activities, the archaeologists were encouraged to interact critically with the system, draw out its limitations and potential, and suggest possible issues connected with the use of the platform (see Figure 29).

Figure 29. AIR on-site
Using the 3D annotation tool embedded into AIR to identify one of the investigation areas at the Gribshunden site. Photograph by Paola Derudas.

Results

The results obtained at Gribshunden underlined the benefits of using a system that encourages a flexible data management approach and incorporates advanced visualization forms. The experiments carried out during the first campaigns demonstrated the crucial impact of 3D web visualization in support of underwater archaeological practice and allowed the identification and implementation of tools for expanding the use of the system towards different field investigations.

The implementation of AIR during the last two investigation campaigns allowed for assessing the system’s potential in (1) encouraging a reflexive approach during the field investigation, (2) promoting discussion, and (3) formulating new interpretations.

Such exceptional results prove the benefits of a system built to promote an archaeological digital curation approach that encompasses all excavation data and archaeological reports.

5.1.5 Additional experiments: closing gaps in visualization

In addition to the four experiments, two additional experiments were conducted to expand the critical evaluation of the 3D visualization components to different excavation contexts.

I developed visualization tests within the framework of two small excavations conducted at a cairn in the area of Bronze Age and Iron Age grave remains, and two Bronze Age cremation urns. The aim was to assess the impact of 3D web visualization on specific archaeological records and how implementing 3D recording technology for supporting field practice encourages new forms of data aggregation, affecting traditional data management structures.

The results of this work were very informative and were considered during the design process of the experimentation carried out at Västra Vång and Gribshunden.

Additional experiment 1: Vambåsa

In March 2019, I joined a field investigation activity at the site of Vambåsa (Blekinge). The small excavation aimed to explore the nature of field system and grave remains from the Bronze Age and earlier Iron Age. The fieldwork, carried out in collaboration with the Blekinge Museum, mainly focused on excavating a cairn to contribute to a better understanding of a cultural-historical local and regional context (Henriksson, 2022b).

The experiment carried out at this site aimed to explore the capacity of IVS to visually describe the dismantling of archaeological structures. In particular, I was interested in understanding at which stage it is necessary to generate a 3D model for accomplishing an informative temporal description of the key elements that compose the feature (see Figure 30).

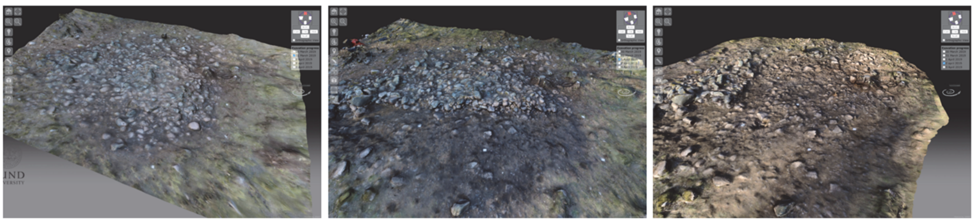


Figure 30. IVS at Vambåsa
The excavation progress at the Vambåsa cairn visualised in the Interactive Visualization System. Images by Paola Derudas.

The experiment once again proved how 3D visualization technology can be used to identify new forms of data aggregation, often not included in more traditional archaeological data modelling systems. The results of this work were considered during the implementation of the 3D editing tool developed in AIR for providing a temporal representation of the archaeological features detected at Gribshunden.

Additional experiment 2: Domsten

In 2020, I had the opportunity of testing a similar approach to document and describe the investigation process of two cremation urns retrieved during the field investigation at the Bronze Age site of Domsten, north of Helsingborg (Skåne). The experiment was conducted in collaboration with Dr Helene Wilhelmson from Sydsvensk Arkeologi, and the investigation was carried out at the Department of Archaeology and Ancient History at Lund University. In addition, before physically excavating the urn, Marcus Söderberg, from the Department of Medical Radiation Physics, Malmö–Lund University, conducted a Computer Tomography acquisition (CT scan) for performing a previous virtual assessment of the materials contained in the urns.

The 3D data identified using the CT scan functioned as a volumetric map to guide the archaeologists during the investigation and determine the best excavation practice to employ. In addition, I used Image-Based 3D Modelling techniques to record each layer of information removed from the urns, providing a set of 3D data to describe the excavation progress (see Figure 31).

I produced 56 3D models (27 for the urn, no. 9000, and 29 for the other, no. 9944). Once generated, the models were published using IVS and were visually organized to illustrate the sequence of actions undertaken during the investigation (see Figure 32).

As in the previous case, the results of this experiment provided important indications concerning the capacity of 3D web visualization technology to develop visual narratives for illustrating unconventional and complex investigation practices. The results of this work were considered during the implementation of AIR, specifically for the adaptation of the platform to the Gribshunden case study.

Figure 31. Urn excavation and 3D documentation
Top: an intensity-modified vacuum cleaner is used to micro-excavate one of the urns; bottom left and bottom right: photogrammetric acquisition of the urns for the production of 3D models to document the excavation progress conducted in the laboratory at Lund University. Photographs by Sydsvensk Arkeologi.

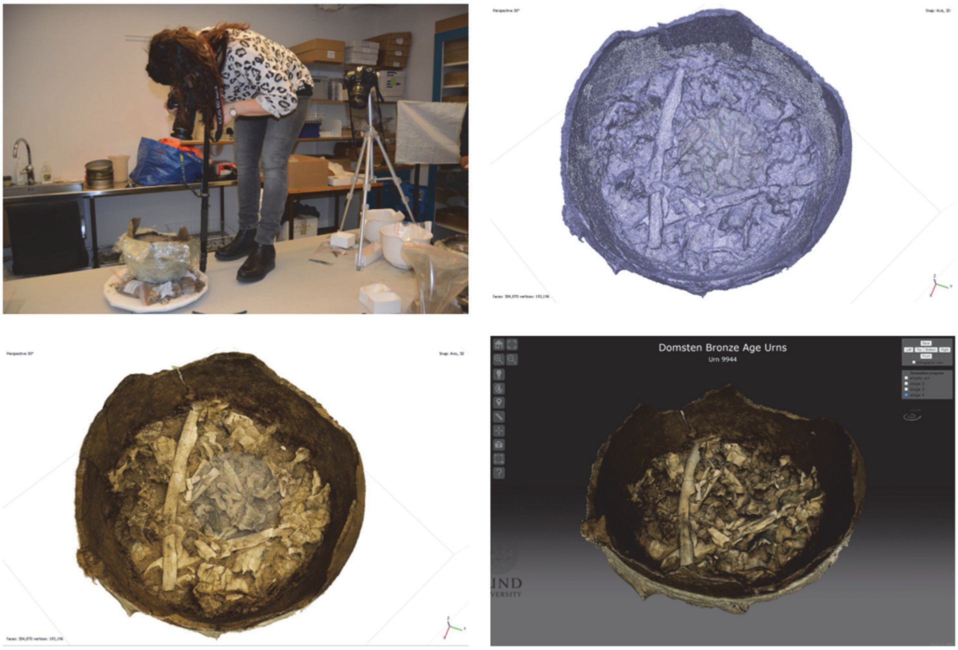


Figure 32. Urn data processing
Data processing of one of the Bronze Age urns micro-excavated in the laboratory at Lund University. Top left: image acquisition for Image-Based 3D Modelling; top right: wireframe 3D model; bottom left: textured model; bottom right: online publication in IVS. Photograph by Sydsvensk Arkeologi; images by Paola Derudas.

5.1.6 Experiment conclusions

Throughout the dissertation project, I worked with many diverse case studies across time (from Mesolithic to the late medieval period), investigation environments (terrestrial and maritime archaeology), institutions (academia- and development-led investigations), and stakeholders (students, researchers, and specialists) who use the reports as the primary means to share the same epistemic goal of creating knowledge about the past (Börjesson, 2017, p. 15).

The research methodology established during this project comprised the development of targeted experiments that addressed various aspects of the research questions posed throughout this work. During the investigation, I collected, processed, interpreted, and archived a large number of archaeological records that led to the creation of multiple operational systems used to assess how the establishment of a solid connection between archaeological archives and scholarly argumentation (the reports) impact archaeological practice.

This approach proved very useful in sketching, developing, and improving flexible solutions customized according to the characteristics of each campaign and stakeholder involved. Furthermore, working with such extensive materials emphasized the importance of establishing documentation and archival practices rooted in long-term sustainability and, more specifically, in the FAIR principles.

Over the years, many different stakeholders used the various platforms created during the project to perform diverse tasks, thereby demonstrating the broad impact and potential of a 3D visual (digital) approach on the cultural heritage sector.

5.2 Evolution and refinement of web publishing systems

This paragraph presents the 3D web platforms developed as part of the activities of this doctoral project. Besides promoting advanced data visualization and interaction, these web publication systems were created to provide archaeologists and cultural heritage practitioners with a digital environment for reviewing, accessing, and (re)using the information and interpretations created during the field investigation process.

The online platforms are presented in their evolutionary aspect, in connection with the research goals of each case study. The description starts with the basic visualization platform, continues with the reporting system, and ends with information system which integrates the 3D visualization platform 3DHOP into the Content Management System Omeka S.

5.2.1 Developing System 1: Interactive Visualization System (IVS)

The first system used in this work, the Interactive Visualization System, is a direct derivation of a 3DHOP visualization page and follows my past experience in publishing archaeological excavation data (Derudas et al., 2018).

The system is a pure-output tool: its purpose is only to present data and information to the target users, who can freely explore the whole dataset, and use the available tools to interact with the 3D models and mapped information, but they cannot add new information or modify the presented content.

Following this, the authoring step is done entirely by hand, and requires familiarity with both the use of 3D tools and data, and of the HTML and 3DHOP tool: ideally, it would be undertaken by the person in charge of the digital documentation of the excavation.

As the needs of different excavations and/or datasets may vary, the general setup of the page may be changed to accommodate specific tools, data arrangement, and additional 3D visualization components. This makes the system quite flexible, but requires an additional step for designing the data access interface, and implementing it. Once filled with the data, the IVS pages are static, i.e., each HTML page contains texts and media files, and directly loads and displays 3D data.

The core mechanic for exploring the excavation dataset exploits the presence of multiple 3D models, each representing a time step of the excavation. Each of these models can be loaded in a 3DHOP scene and presented as a layer that can be shown/hidden to follow the progress of the excavation (see Figure 33).

The basic turntable-plus-panning navigation is complemented with canonical views and a compass, which provides an immediate and familiar visual feedback. To help the final user to explore the dataset both spatially and temporally, specific points of view and combination of layer visibility can be added to the navigation panel. Information that is localized on the 3D surfaces may be added as geometric hot spots. All these functionalities are based on the existing features of 3DHOP and are connected to interface elements of the web page via scripts (see Figure 34).

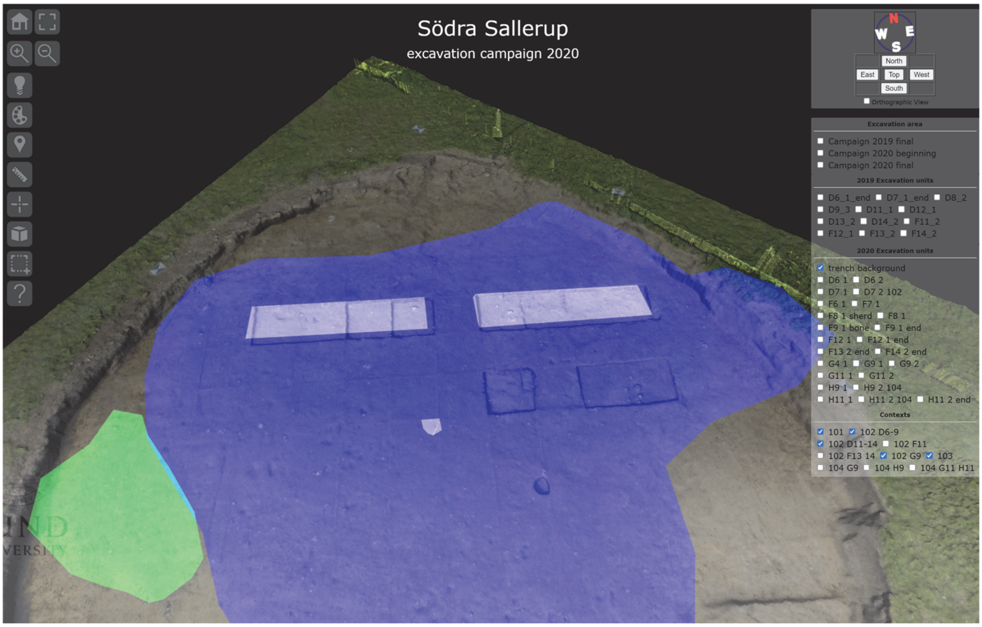


Figure 33. IVS at Södra Sallerup
The context extensions superimposed onto the excavation area as excavated in 2019 and 2020. The panel at the right allows the customization of the visualization of the different models (trench, excavation units, and contexts). Image by Paola Derudas.

The IVS pages are, in the end, quite simple: 3DHOP is the main component, used to display the 3D models and provide the interaction and measurement tools; the rest of the interface is made using HTML5, with minimal custom CSS and JavaScript code.

The result is client-side only, i.e., it does not require any server capabilities (computation, database, and running services), just some disk space in a web server. This makes the system much easier to install, and lightweight.

Figure 34. IVS components

The Interactive Visualization System layout: (a) the 3DHOP panel tools to customize the 3D models' visualization, take measurements, pick co-ordinates, cut through planar sections, and finally save screenshots of the 3D scene; (b) navigation panel with the compass, the canonical views, and the orthographic view; (c) 3D model panel, to set the visibility of the uploaded 3D models, sorted by typology and excavation campaign. Image by Paola Derudas.

5.2.2 Developing System 2: Interactive Reporting System (IRS)

With the Interactive Reporting System, the paradigm moved from a pure presentation of the excavation data towards a more narrative approach. Differently from the IVS, it was important that this narrative component could also be directly authored by archaeologists who lack experience of 3D data manipulation and HTML development. For this reason, excluding the initial step of the preparation of 3D models, the authoring step has been fully integrated in the interface, following a

WYSIWYG paradigm (What-You-See-Is-What-You-Get, i.e., while the user is composing the 3D scene and the report, everything will look and act as it will look and act in the final published version). The editor lets the archaeologist compose the 3D scene using the available 3D models, add the finds to the scene, write the report block by block, and add to each block predefined points of view, as well as images and documents (see Figure 35). This process worked in a hybrid local-authoring plus online-publishing way: in this way it was not necessary to set up complex server storage and interaction mechanisms, thus simplifying the authoring and publishing step, at the cost of some manual work.

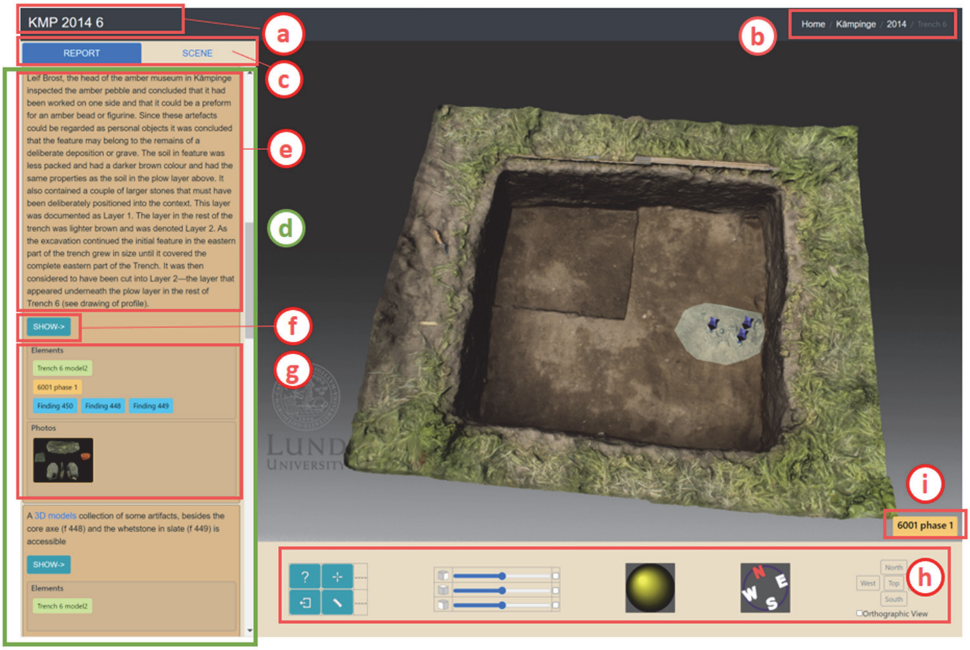


Figure 35. IRS components

The Interactive Reporting System components: (a) heading of the excavation node report; (b) the site menu; (c) Report and Scene tabs to access the report and display the 3D models and elements used to represent the trench. The report block (d) encompasses the narrative/text (e), the 3D scene button (f), and the report block components displayed in a box (g). The centre-right bottom panel (h) provides the scene's measurement, rendering controls, and navigation tools. Once the information tool is activated, the content hovering on is detected (i). Image by Paola Derudas.

As shown in *Paper I*, it has been possible, with a reasonable effort, to train an archaeologist in the use of the editor and have them fill out the yearly reports with appreciable results.

A core component of the system was the data structure that was used to describe the archaeological report: this structure was filled by the WYSIWYG editor and saved in JSON format; the editor could later on be used to modify or expand the reports. In the published version of the IRS, the web pages of the reports are dynamically created starting from the authored report data structure. This makes it easier to expand and update the content of the system, as there is a clear distinction between the information (the 3D models, media files, and the JSON reports) and the visualization page (HTML and JavaScript code).

Conversely, the index and most of the introduction pages of the IRS website, of course, are static and hand curated (see Figure 36). The final published system is still client-side only, as the interaction between the pages and the final user only rely on the webpages and on the authored data.

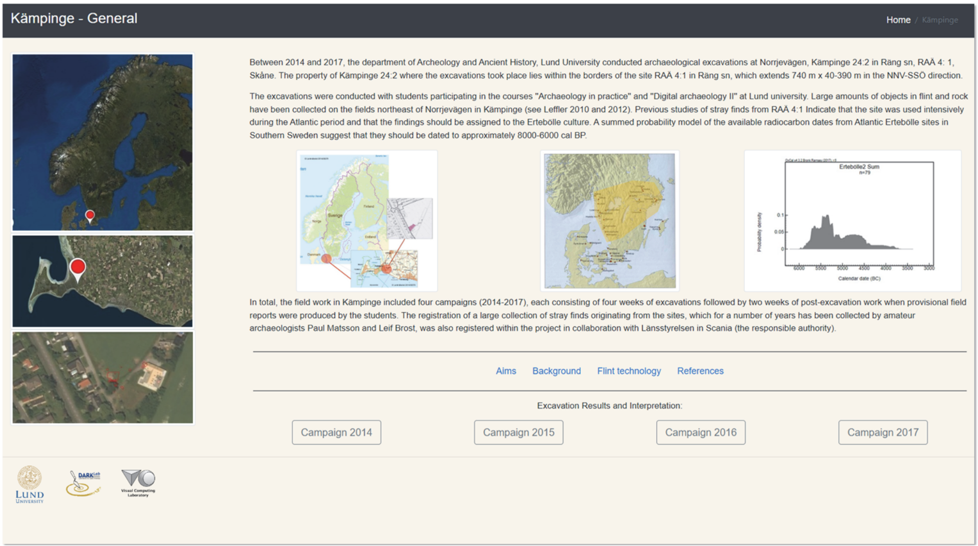


Figure 36. IRS introduction page
The introduction pages of the Interactive Reporting System are static and provide aceess to other static pages that add information on the project (Aims, Background, Flint technology, and References) and to the interactive reports of the different excavation campaigns. Image by Paola Derudas.

The design of the JSON report structure was based on a careful analysis of yearly archaeological reports and guided the implementation of all the features and workflow of this system. The formalization process of this structure was also the base of the design and development of the following system, AIR, which evolved directly from this one, IRS.

In terms of underlying technology, IRS still heavily relies on 3DHOP for 3D visualization and interaction, but also uses other web development libraries and components, such as the Bootstrap framework for the interface and appearance.

The addition of the integrated editor and of the dynamic creation of the pages made this system much more complex with respect to IVS and moved the activity towards the idea of using this tool to help organize and structure the available archaeological data in a new form, instead of just statically presenting an already structured dataset.

5.2.3 Developing System 3: Archaeological Interactive Report (AIR)

The next logical step of this evolution was to move towards an information system (Katsianis, 2012) based on a Content Management System (CMS) tool, where to ingest all the available information, possibly enriching it with semantic-mapped metadata, and providing an even more integrated way to arrange it in the proper narrative and presentation form. To do so, it was necessary to work with a server-based online tool, able to provide structured data management, authentication and user profiling, data storage, and metadata management.

It is with these considerations that the third system, the Archaeological Interactive Report (AIR) was designed. AIR is a user-centred and easy-to-use tool for archaeological data curation to use across the life cycle of data. It overcomes the limitations of archaeological data fragmentation and dispersion by combining the data analysis and management approach of GIS with the 3D content interactive visualization approach of 3DHOP (see Figure 37). AIR is an online system for collecting and managing data from archaeological excavation and for writing dynamic archaeological reports employing structured data to relate to the web of data and adhere to the FAIR principles.

Figure 37. System 3
AIR's logic and structure integrates the 3D visualization potential of 3DHOP into the structured, flexible and semantic-oriented data model of Omeka S, opening, this way, to the FAIRness of the data. Image by Federico Nurra (CC-BY 4.0).

The design and development of the AIR platform are the results of collaborative work with the French National Institute of Art History (INHA), characterized by the strong expertise of the Digital Research Service (SNR) in structuring, managing, and publishing cultural heritage documentary data (Nurra & Courtin, 2020).

The work started with data structuring by defining a conceptual model (Katsianis, 2012, p. 5), defining the database entities (*Classes*), and their relationships (*Properties*). In order to address the methodological requirements of archaeological documentation, a flexible compatibility model that considers a semantic alignment toward the most diffused shared ontologies in the cultural heritage domain was chosen (see Figure 38).

After defining the conceptual data model, it was possible to identify the most suitable CMS for the publication of archaeological documentation data and metadata. The Omeka S CMS was chosen for its flexibility in data structuring, personalization of web exposition, and availability of a robust REST API for semantic data exposition and possible adherence to the FAIR principles.

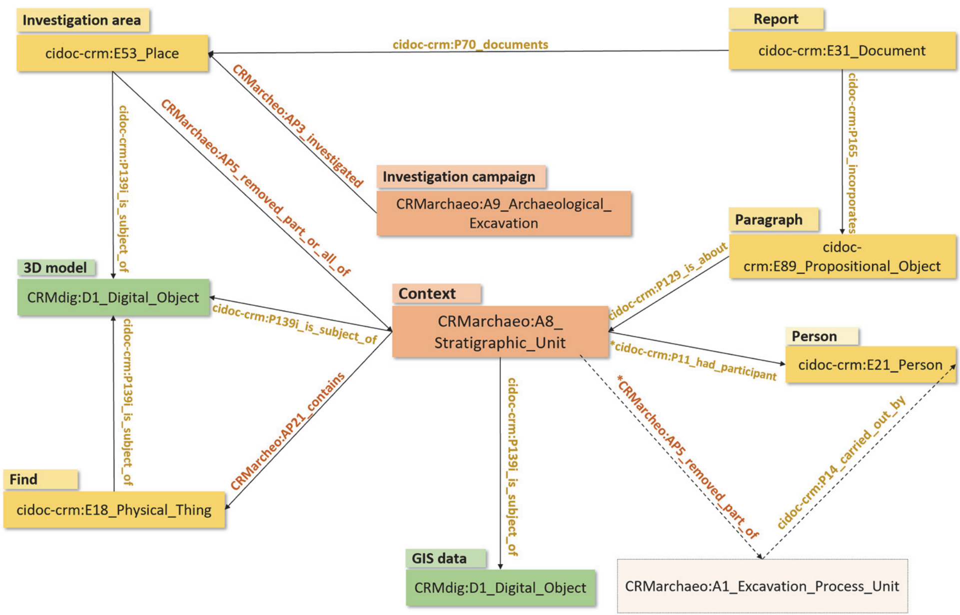


Figure 38. System 3 conceptual model

The conceptual data model illustrates items, described by ontological classes, interconnected through ontological properties. Different reference ontologies are displayed by different colours. The dotted lines indicate connection with a bridging class that allows the respecting of the CIDOC CRM conditions. Image by Paola Derudas.

In a basic installation of Omeka S, some ontologies were imported via the RDF import tool, together with open-source modules developed by the Omeka S project community; through the Omeka S resource templates, the entities' data structure framed through the conceptual model was implemented. A new Omeka S theme was designed to associate the structured data to its media and the 3D models; tailoring the visualization of the entities to the archaeologists' requirements by integrating the 3DHOP code on an HTML page and linking the JavaScript variables to the MySQL database values, through PHP REST.

The HTML visualization templates of the entities are created through a server-side PHP recall of data already stored in a MySQL database. They are produced after the archaeological features such as contexts and artefacts have been registered and data accessed and reviewed. Some function loops interrogate the database searching for content to call out the report's components, such as the paragraphs. In this way, the web page visualization of the report is based on the displayed content. The most challenging task was developing the integration of the 3D visualization components inside the Omeka S theme.

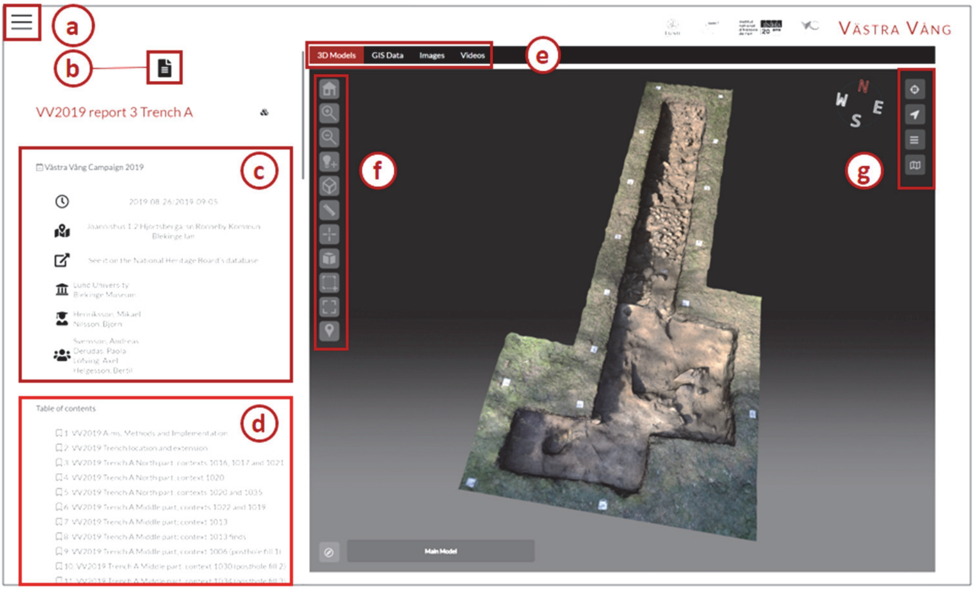


Figure 39. AIR report components
The archaeological report in AIR: the menu (a) with the report icon (b); metadata grasped from the Investigation Campaign (c) and the paragraph titles (d). The media canvas and tabs (e) to access 3D models, GIS data, Images, and Videos. The media canvas provides measurement and visualization tools on the left side (f) and 3D visualization tools on the right (g). Image by Paola Derudas.

To achieve such a goal, JavaScript libraries were used for the 3D visualization aspects and Leaflet JS for the geographical data; the two libraries' variables were analysed to set the visualization of each Omeka S database entity and its metadata (see Figures 39–42).

In the case of the paragraph, the user can choose the 3D content by combining multiple models and defining a specific scene in the 3D canvas setting the 3DHOP parameters and using a dedicated entity that allows it, the 3D scene. Furthermore, to control the 3D visualization aspects, a 3DHOP dedicated ontology, "tdhop", was created. To allow archaeologists to graphically represent the artefacts in the 3D space, we bound a 3D model to the artefact entity in the form of a sphere every time co-ordinates are supplied (i.e., the 3D model/artefact entity is spherical). Each category was associated with a colour-array in order to be visualised according to their group (see Figure 41).

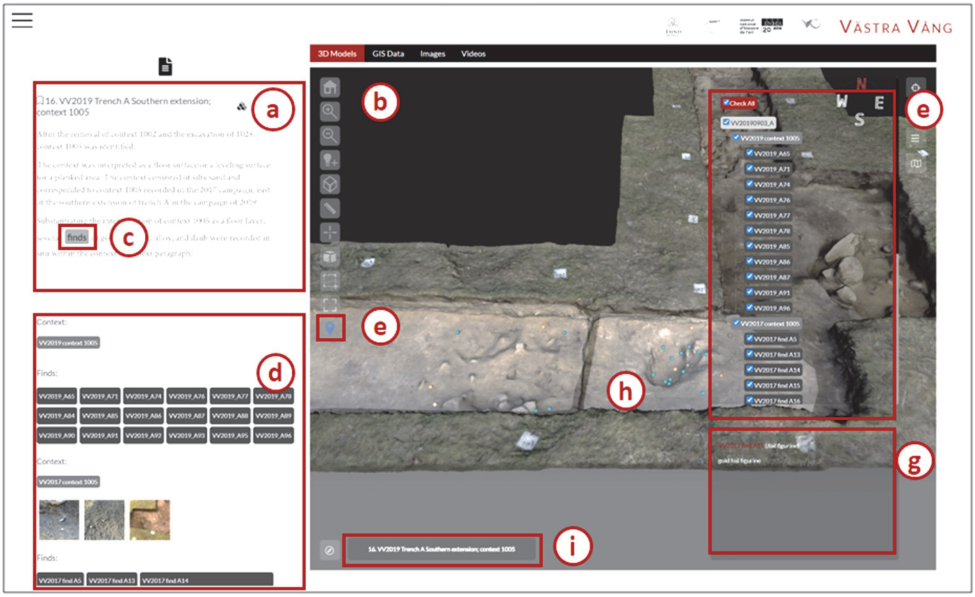


Figure 40. AIR paragraph components
The paragraph layout seen in the report. Descriptive components (a) and 3D visual representation (b). The 3D scene buttons change the view of the visual components (c). The elements composing the paragraph are accessible either through the paragraph elements box (d) or within the 3D canvas, once activated through the information button on the left menu (e) (g). The model visibility menu controls the 3D components view (f). The artefacts visualised in their find-spot in the trench are represented as colourful 3D spheres according to their category material (h). The title of the 3D model paragraph is displayed at (i). Image by Paola Derudas.

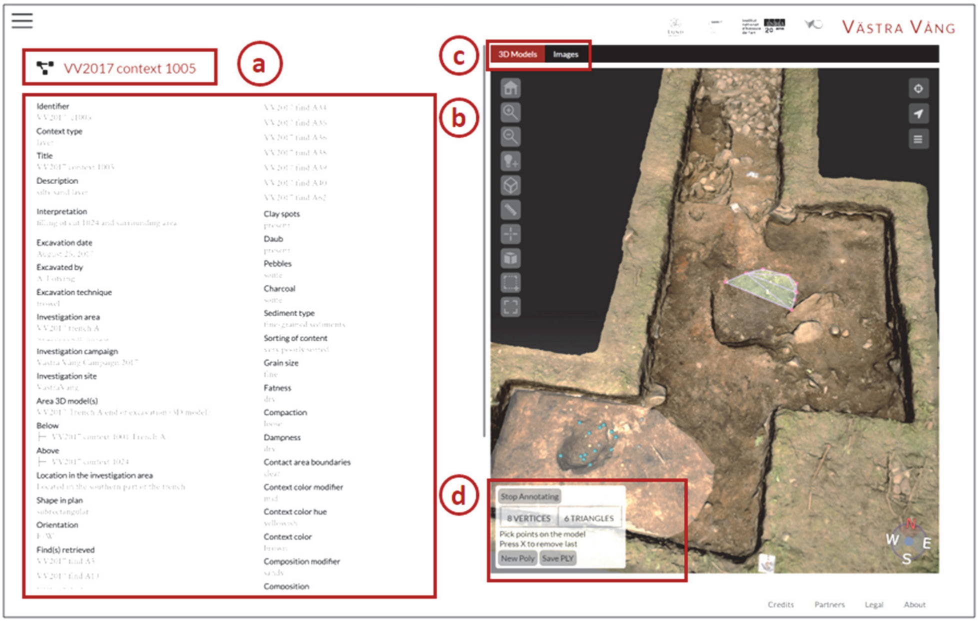


Figure 41. Context recording sheet components
The context recording sheet, identified by icon and title (a). Metadata is on the left (b); the available visual media is displayed in the canvas at the right (c). 3D annotation tool (d) allows drawing the extensions of the contexts directly onto the 3D model. Image by Paola Derudas.

The AIR's semantic structure complies with the FAIR principles and allows the entire dataset (data-photographs-models) to be exported for archiving purposes in a semantically structured way, transcending the platform life and enhancing data and content interoperability. However, due to the excavation dataset's complexity, a simplified data model was designed to create an easy-to-use tool for archaeologists. Shortcut properties were defined to link some classes, such as the context and the archaeologist excavating it, because CIDOC CRM is an event-oriented model and does not permit a direct connection between them. A future RDF exposition through a CIDOC CRM alignment for each property of our model will be made. (see Figure 43).

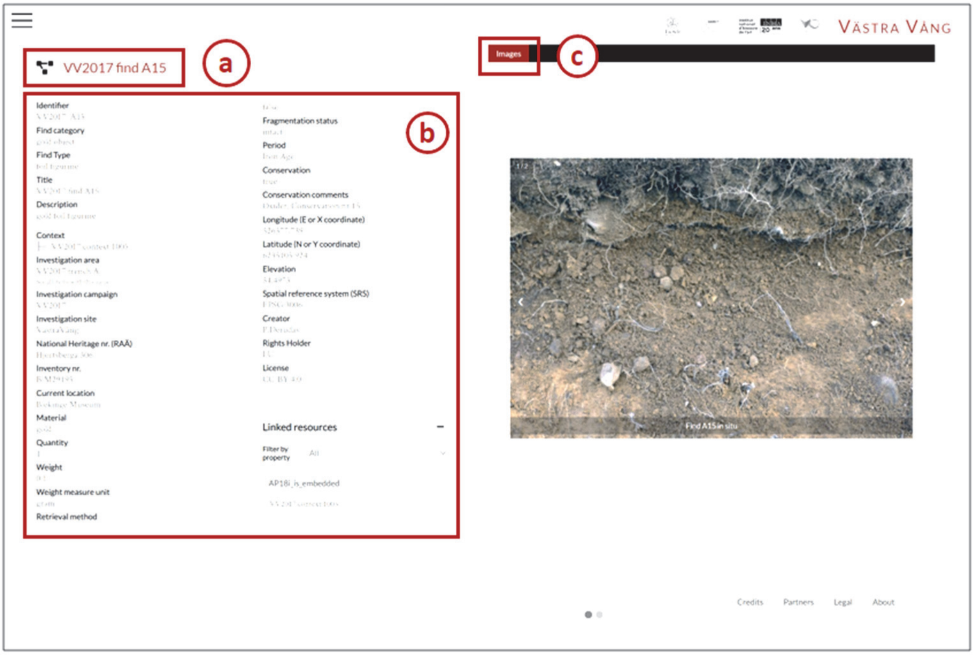


Figure 42. Find recording sheet components

The find recording sheet, identified by icon and title (a). It displays the metadata (b) on the left side and the media on the right side (c), as with the context sheet. In this case, no 3D models are available, and a photograph of the *in situ* artefact is displayed. Image by Paola Derudas.

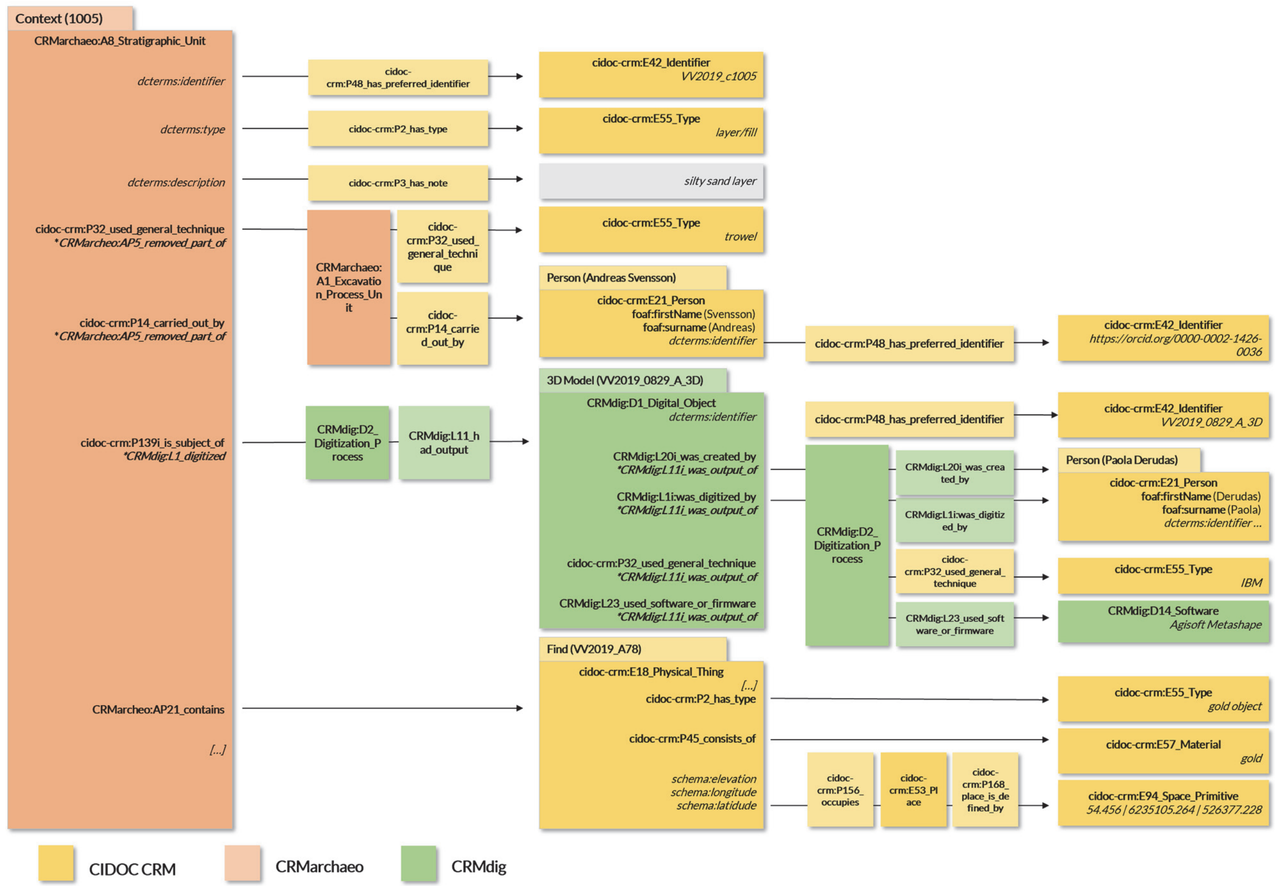


Figure 43. System 3 logical model and future mapping
An extract of the metadata schema of AIR describing the item *context* and its connections. The model was simplified with shortcut properties to connect some classes. A future RDF exposition through a CIDOC CRM alignment will provide a correct mapping. Image by Federico Nurra (CC-BY 4.0).

Significant attention was devoted to the user experience (UX) and ergonomic topics: to customize the web page appearance, a specific CSS was designed based on a three-colour scheme for easier reading. Material design[2] inspired graphic representation of the main functionalities and making the content exploration as intuitive as possible: all the entities were attributed pictograms and icons to allow their immediate recognition. The website contents are also accessible via a dynamic table of contents that is easy to customize from the Omeka S back end.

Another relevant aspect considered in the UX was the system responsivity mode: the goal was to provide archaeologists with comfortable use through portable devices, considering fieldwork requires such kinds of instruments (see Figure 44).

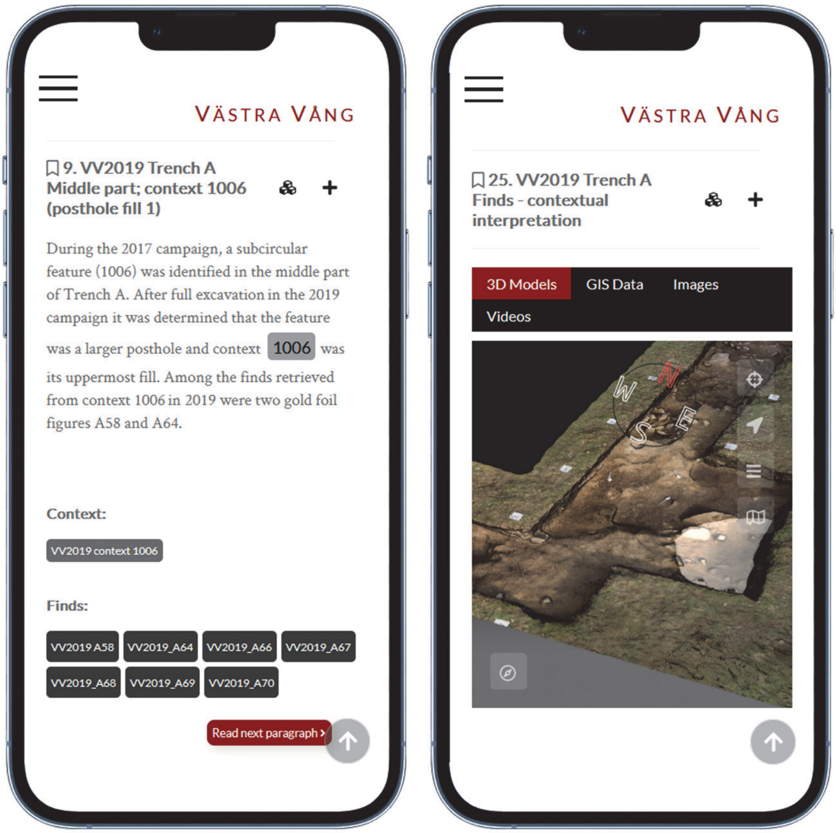


Figure 44. AIR responsivity
The responsive design AIR is apparent in the Västra Vång report visualised using a smart phone. Image by Federico Nurra (CC-BY 4.0).

[2] https://m2.material.io/design/introduction

5.3 Assessment: applying the three systems to four case studies

The aim of this PhD is to identify and implement valuable specific systems to support archaeologists throughout the investigation process. The large number of participants in the field trials and the variety of investigations carried out during the project necessitated the use of different evaluation methods for the assessment of the project results, and these were crucial to obtain feedback for continual design improvement and implementation.

During the project (1) field notes were used to collect critical feedback and observations, (2) anonymous questionnaires were employed to collect feedback on how the platforms impacted the activities of the different users working on-site, and (3) a self-assessment tool was used to evaluate the level of FAIRness of the latest platform (AIR) developed.

5.3.1 Case study 1: Kämpinge

The experiments developed at Kämpinge aimed to combine dynamic narratives with advanced online 3D visualization methods to conceptualize and implement a system capable of facilitating the (re)interpretation of data.

I observed and recorded how the director of the field investigation, while using the system to report the results of the various excavations that took place between 2014 and 2017, used the 3D data in IRS to generate the reports. During the experiment, I held a series of discussions with the field director and obtained valuable insights into the use of 3D visualization tools to aid field interpretation. I was interested to see if such a practice suggested different interpretations and how the use of the platform might affect he construction of the narrative.

During the COVID-19 pandemic, the system was also used during a field course to provide students with a virtual proxy to observe and learn how to identify and manage the various features during the field investigation process. The students evaluated the system through an anonymous course evaluation questionnaire. As the platform was the central material used during the course, I used the course evaluation questionnaire to gather wider feedback on how the system affected the students' understanding of fieldwork.

The questionnaire was distributed to 10 students taking part in the field course. The students were asked to state their level of satisfaction with the course, and assess the relevance of the subject matter, the time spent using IRS, and its limitations and potential. The responses underlined their high satisfaction in using IRS and combining it in combination with more traditional tools and methods.

5.3.2 Case study 2: Södra Sallerup

The experiments developed at Södra Sallerup aimed to evaluate the capacity of 3D web visualization to support the process of field investigation and to determine how the presence of detailed 3D documentation can facilitate interpretation.

The evaluation was carried out by means of an anonymous questionnaire designed to obtain critical feedback on (1) the use of the system for checking stratigraphy, (2) the examination of previous excavation data, and (3) the production of graphical material for use in the archaeological report.

The questionnaire was distributed to the 10 students taking part in the course, and it comprised 21 questions, of which 15 formulated as multiple-choice answers and six as free text. Unlike the standard course evaluation questionnaire used in Kämpinge, the evaluation form used in Södra Sallerup included questions about the use of the 3D visualization system in the field and how the presence of such a tool affected the perception of the site.

The questionnaire was also used to ask students to give their opinion on how the system had affected the process of knowledge production. Although the students' evaluation was generally positive, it also highlighted the inability of the system (IVS) to provide complete access to the entire archaeological records.

5.3.3 Case studies 3 and 4: Västra Vång and Gribshunden

The evaluation of the experiments developed in Västra Vång and Gribshunden was undertaken by combining several evaluation methods. The system developed during these experiments was used to evaluate and complete most of the research questions posed during this PhD project. Specifically, I was interested in the following:

1. Assessing whether the system could be used by multiple users to report archaeological investigations and access the excavation archive;
2. Observing how the use of such a new documentation system affected archaeological practice during excavation and post-excavation activities;
3. Assessing the degree of FAIRness of the system and its potential to reach a wider community of practitioners.

An initial evaluation was carried out by means of field observations and the collection of feedback from staff using the system to record archaeological features encountered during the survey.

The system was also evaluated through an anonymous questionnaire circulated to archaeologists and professionals from the academic and commercial sectors who were asked to access and use the online report available through AIR and to provide critical feedback on the structure, interaction, and level of clarity of the information reported online.

The questionnaire was also designed to assess AIR's ability to link reports and datasets stored in the system. The questionnaire was distributed to 12 practitioners and comprised 20 questions, of which 16 were yes-or-no questions, seven with detailing comments, and two as free text.

The questionnaire started with an introductory video on how to use AIR. Users were then asked to read and interact with the online report before answering the questions. The questions were designed to assess information on accessibility, quality of interaction, and the link between the report and the data archive.

The level of FAIRness of AIR was assessed in terms of openness and alignment with open science using the "Self-Assessment Tool to Improve the FAIRness of Your Dataset" (SATIFYD) developed by the Dutch Data Archiving and Networked Services (DANS). Based on this assessment, AIR has an average FAIRness potential of 63%.

6. Research outputs

6.1 Publications

This thesis has produced two different types of outputs, namely peer-reviewed articles, and web publishing systems. The articles address the various research questions presented in the thesis and engage with the specific case studies that were selected for the experimentations described above. Even though they are published as independent works, they result from the theoretical, methodological, and developmental discussion that has been developed during the PhD project.

6.1.1 *Paper I:* Sharing Archaeological Knowledge. The Interactive Reporting System

This article was published by the *Journal of Field Archaeology*, 2021, VOL. 46, NO. 5, 303-315; it was co-authored with Nicolò Dell'Unto, Marco Callieri, and Jan Apel.

Abstract

This study describes the development of a digital reporting system designed to provide archaeologists with a dynamic and interactive 3D web platform that can be used for describing in great detail records and activities undertaken across a multi-year field investigation campaign. The system was used to compose the archaeological report of a multi-year investigation and employed during the pandemic crisis for supporting digital courses in archaeological practice; the paper also reports the preliminary results of the use of this platform within teaching activities. Unlike other web solutions, this system supports an assisted publication of archaeological contents that integrates a 3D visualization system in the reporting process, exploiting the communicative potentials of 3D models and the web. This study represents a contribution to research on sustainable forms of management and publication of archaeological contents and their reuse and sharing.

I designed and co-ordinated the experiment. I co-designed the system used during the experiment, co-ordinated the article, developed the structure, and wrote the "Introduction", "Methods and Materials", "Results and Discussion", "Conclusions and Further Work" sections. In addition, Jan Apel participated in the experiment and revised the historical information in the “The Archaeological Site of Kämpinge” and “Testing the System in a Classroom” sub–sections in the “Methods and Materials” section. Nicolò Dell’Unto supported the experiment by providing insights on the work conducted in Kämpinge during previous excavation campaigns. He contributed to the “Context and Aim” section. Marco Callieri implemented the system used during the experiment and contributed to writing the “Methods and Materials” section.

6.1.2 *Paper II:* Expanding Field-Archaeology Education. The Integration of 3D Technology into Archaeological Training

This article was published by the journal *Open Archaeology* 2021; 7: 556-573, open access; it was co-authored with Åsa Berggren.

Abstract

This contribution analyses and discusses the use of 3D technology in education and learning. Basing the discussion on a case study performed during two seasons of a field school for 1st-year archaeology students, we explore how to expand traditional didactic programs by developing and testing a web-based system for educational purposes. We examine how these technologies can be used as educational means and supporting tools during an excavation; how universities can incorporate these technologies into pedagogy. We investigate whether the combination of these technologies with a successful pedagogical theory could promote students’ comprehension of the reflexive approach and engagement with the interpretative process.

We introduced the students to a complete excavation methodology, including excavation, documentation, data management, and interpretation. Alongside the traditional documentation, a digital approach was added, with 3D technologies and an Interactive Visualization System that allows fully three-dimensional reasoning from the beginning and throughout the whole archaeological process. Preliminary results show that students easily incorporate 3D documentation into their toolbox for analysing and visualising the material and understand both the possibilities and limitations of the system. However, we identified some limitations in the students’ use of the system. Together with the students’ feedback, we will use them to develop it further and discuss its use in education.

I designed, developed, and implemented the 2019 and 2020 IVS. Together with Åsa Berggren, I designed the questionnaire. We both contributed to all sections; however, I wrote most of Sections 1–4 and 6, while Åsa Berggren wrote most of Section 5.

6.1.3 *Paper III*: Archaeological Publication Systems: Which route to take? A compass for addressing future development

This paper was published in the Proceedings of the 26th International Conference on 3D Web Technology, Web3D ’21, November 8–12, 2021, Pisa, Italy; I am the only author of this article. The paper analyses a selection of online publication systems for the publication of archaeological content and discusses their significance in supporting archaeological data management and practice.

Abstract

The recent diffusion of new formats of archaeological publication systems results from ad hoc solutions conceived and realized for serving specific communication needs. These new formats are customized for facilitating the fruition of specific archaeological information and can be tailored and structured for hosting datasets and results. Unlike standard publications, they do not represent the final result of the investigation but rather a dynamic public space in which different interpretations can be revised and formulated. A review of the available online publication systems for Culture Heritage, with a focus on the publication systems the author worked with, can help define their potential advantages and flaws and steer the design and development of further advancements.

6.1.4 *Paper IV*: New AIR for the archaeological process? The use of 3D web semantic for publishing archaeological reports

This article was submitted to the *Journal on Computing and Cultural Heritage* to be published in the special issue on Semantic web and ontology design for cultural heritage. A revised version of the manuscript was sent to the editors, who recommended it for publication with minor revision. It was co-authored with Federico Nurra and Andreas Svensson.

Abstract

The management of archaeological excavation data has been the subject of scientific debate in the last decades: critical elements have been identified, such as maintaining analytical data and the derived knowledge entangled, and other relevant aspects, like data curation, accessibility, and long-term preservation, have emerged. This study describes, illustrates, and evaluates the use of the Archaeological Interactive Report (AIR), a cutting-edge information system designed to manage excavation data that is oriented toward the 3D web semantics. AIR is a web platform for recording archaeological investigations live, an online archive that incorporates the complete dataset of the investigations, and a multimedia visualization system providing a 3D environment for data analysis and assemblages, testing interpretation hypotheses, and publishing dynamic editorialization outputs. AIR is applied and evaluated within the

case study of Västra Vång (south-eastern Sweden), demonstrating that it is possible to use a flexible ontological data model tailored to the archaeologists' needs.

I designed and co-ordinated the experiment. I co-designed the system used during the experiment, co-ordinated the article, developed the structure, and contributed to "Introduction", "Methods and materials", "Results and discussion", "Conclusions", and "Further work" sections. In addition, Federico Nurra supported the development of the system's logical model and its metadata schema; he contributed to writing the "Implementing AIR" section. Andreas Svensson, who participated in validating the system and experimenting with AIR as a fieldwork documentation tool, wrote the archaeological information in the introductory section "The site of Västra Vång: a case study for developing digital archaeology".

6.1.5 *Paper V*: Managing data from maritime archaeology investigations: AIR at Gribshunden

This article was submitted to the *Proceedings of the Nordic Conference for Maritime Archaeology IV* held in Roskilde-Denmark, between 5 and 7 May 2022; it was co-authored with Brendan Foley.

Abstract

Maritime archaeology excavations, even in a more complex environment, have the same objectives and requirements as terrestrial ones: documenting digging operations to analyse data in the best way, interpreting it, and producing new knowledge for the benefit of multiple communities. 3D documentation and management methodologies have widely spread among practitioners; however, 3D comprehensive tools for scholarly publications still require development.

This paper fits in the discussion on archaeological data management and its need to encompass every aspect of the archaeological practice (Kansa and Kansa, 2021). It presents the evolution of the documentation and data management strategies employed within the multidisciplinary project at the shipwreck site of Gribshunden, profoundly conditioned by the project's goals to optimize collection and analysis of the project's multidisciplinary nature. The use of the Archaeological Interactive Report (AIR) represents the most suitable solution for achieving such goals, as it addresses the issue of scattered data and allows for maintaining the connection between archaeological datasets and their interpretation and publication, which is crucial for performing archaeological Digital Data Curation (Dallas, 2015).

I conceptualized the manuscript, wrote and revised it. Brendan Foley wrote section 2.1 and edited the manuscript.

6.2 Web publishing systems

In addition to the papers, the web publishing systems (IVS, IRS, and AIR) described in the previous sections are outputs of the present work: they have been adapted to the specific case studies and published online in six different instances of the use of the systems (see Figure 45). They are made public through the website of Lund University's Digital Archaeology Laboratory (DARKLab)[3]. Some systems are currently used by members of the Gribshunden and Västra Vång projects, as well as in various higher education courses (ARKA 22 at Lund University, ARA704-15957 at Stockholm University).

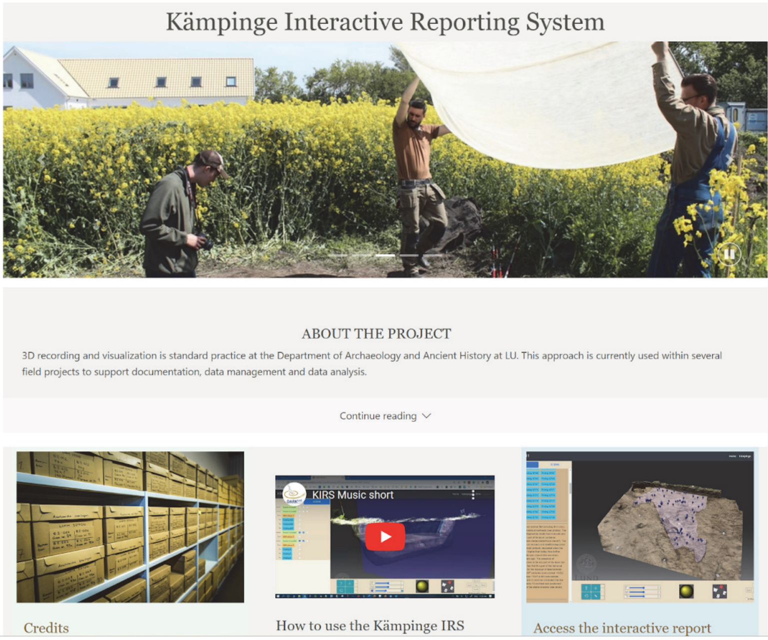
CASE STUDY	IVS	IRS	AIR
Kämpinge	yes	yes	no
Södra Sallerup	yes	no	no
Västra Vång	yes	no	yes
Gribshunden	yes	no	yes

Figure 45. Case studies and systems
Overview of the systems mapped onto the case studies.

[3] https://www.darklab.lu.se/digital-collections/dynamic-excavation/

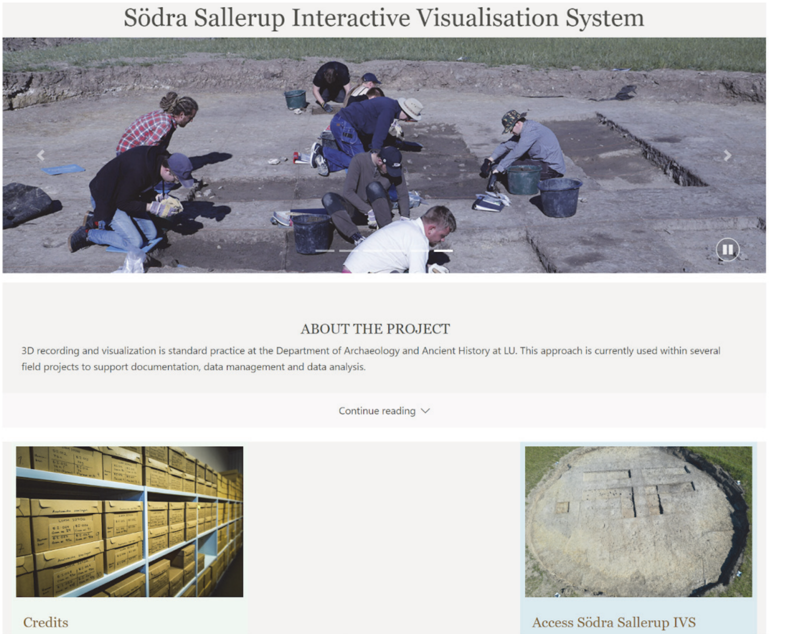
6.2.1 System 2: Interactive Reporting System at Kämpinge

Interactive Reporting System



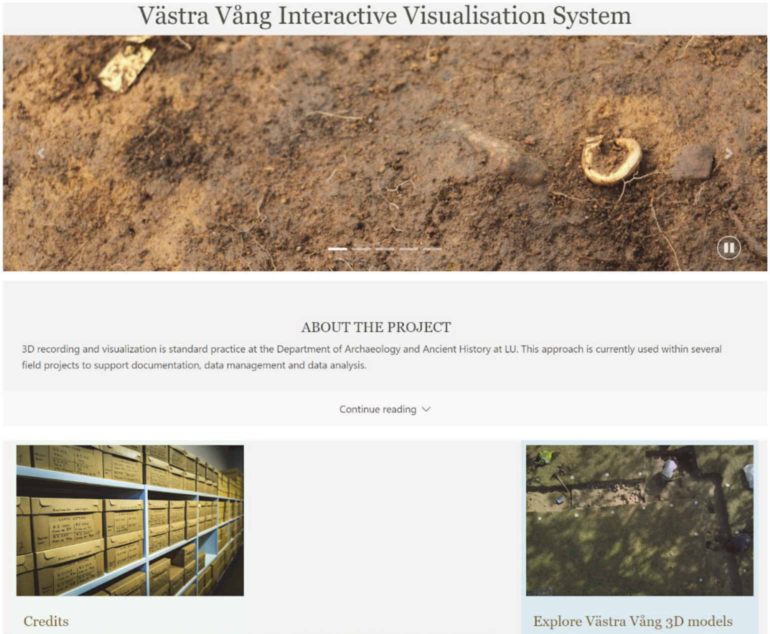
year	2018-2019
project	Kämpinge
description	The Kämpinge IRS is available online through the Lund University Digital Archaeology Laboratory. The web platform includes data collected across four years of investigation at the Mesolithic site of Kämpinge. Once the Kämpinge IRS was completed, it replaced the Kämpinge IVS in the server
link	https://www.darklab.lu.se/digital-collections/dynamic-excavation/kampinge

6.2.2 System 1: Interactive Visualization System at Södra Sallerup

Interactive Visualization System	
	
year	2019, 2020
project	Södra Sallerup
description	The Södra Sallerup IVS is available online through the Lund University Digital Archaeology Laboratory. The web platform includes data collected across two excavation campaigns at Södra Sallerup: textured 3D models of the excavation area and the excavation units; 3D models of the contexts documented
link	https://www.darklab.lu.se/digital-collections/dynamic-excavation/sodra-sallerup

6.2.3 System 1: Interactive Visualization System at Västra Vång

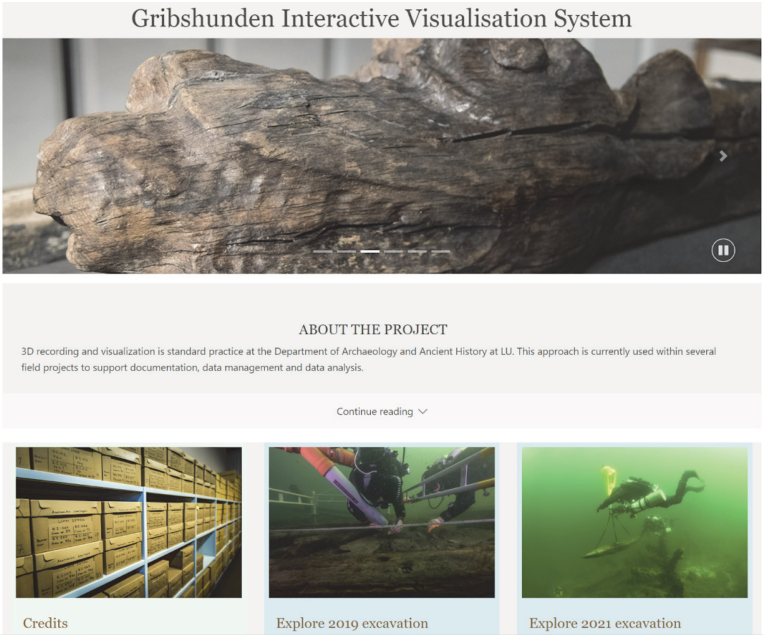
Interactive Visualization System



year	2019
project	Västra Vång
description	The Västra Vång Interactive Visualization System was published in 2019, and it is available online through the Lund University Digital Archaeology Laboratory. The web platform includes a selection of 3D features and finds excavated in 2017 and 2019
link	https://www.darklab.lu.se/digital-collections/dynamic-excavation/vastra-vang

6.2.4 System 1: Interactive Visualization System at Gribshunden

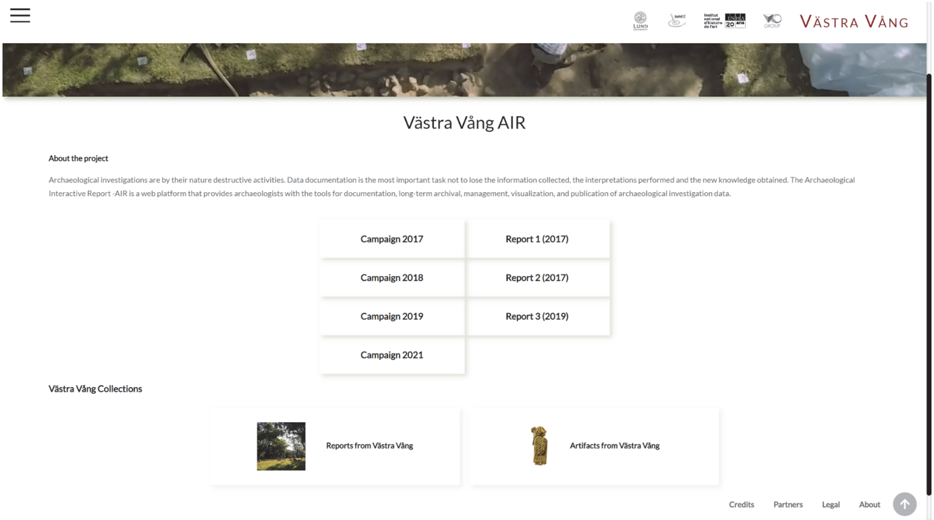
Interactive Visualization System



year	2019, 2021
project	Gribshunden
description	The Gribshunden Interactive Visualization System was published in 2019 and it is available online through the Lund University Digital Archaeology Laboratory. The web platform includes the 3D features and some of the artefacts documented during 2019 and 2021 excavation campaigns
link	https://www.darklab.lu.se/digital-collections/dynamic-excavation/gribshunden

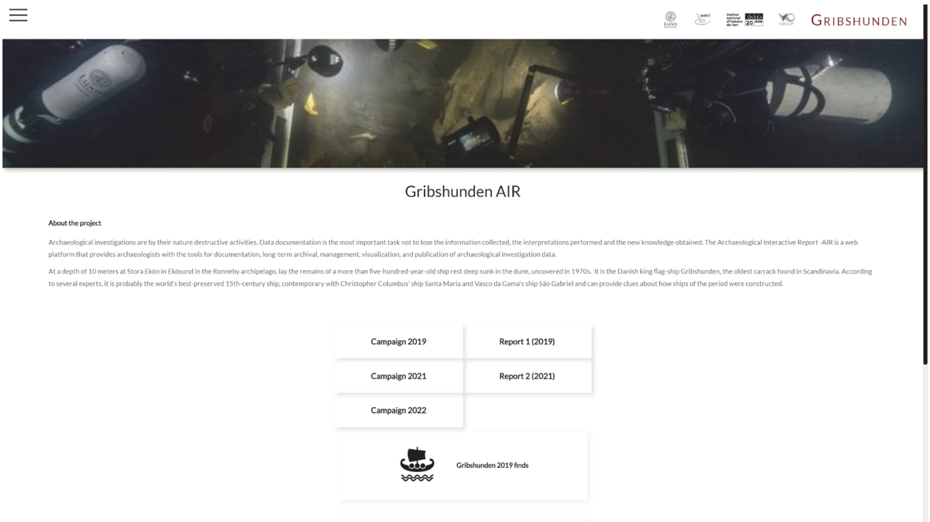
6.2.5 System 3: Archaeological Interactive Report at Västra Vång

Archaeological Interactive Report



year	2021–
project	Västra Vång
description	The Västra Vång Archaeological Interactive Report website was published in 2021, and it is available online through the Lund University Digital Archaeology Laboratory. The web platform allows access to the complete dataset collected during the excavations carried out at the hill-site of Västra Vång and stored in the online archive (trenches, contexts, artefacts, samples, 3D models). It also includes dynamic archaeological reports enriched with multiple media built using the entities already archived in the system
link	https://omeka.ht.lu.se/s/vastra-vang/page/home

6.2.6 System 3: Archaeological Interactive Report at Gribshunden

Archaeological Interactive Report	
	
year	2021–
project	Gribshunden
description	The Gribshunden Archaeological Interactive Report website was published in 2021, and it is available online through the Lund University Digital Archaeology Laboratory. The web platform includes a copy of the 2019 report rewritten exploiting AIR's ability to enrich it with 3D models of features, weapons, and artefacts already archived in the system
link	https://omeka.ht.lu.se/s/gribshunden/page/home

7. Meta-analysis: critical evaluation

The purpose of this chapter is to provide a deeper critical evaluation of the work undertaken at the specific sites which then supports a broader critical evaluation of the overall results and their significance to the wider discipline.

7.1 Evaluation of site-specific insights

This subsection critically evaluates how the experiments conducted at each site selected as a case study addressed the site-specific research questions. For each experiment, the overarching research question is presented, followed by a critical discussion and assessment of the results.

7.1.1 Experiment 1

RQ: How effectively can 3D web data management systems report archaeological investigations reusing data from previous investigations?

The first experiment proved the effectiveness of a system such as the Interactive Reporting System that writes a dynamic report where the text and the virtual space are interrelated, by combining 3D models and other media. The four-year excavation dataset was reprocessed and reused to write the Kämpinge report, demonstrating the system's reliability when used off-site.

Writing the Kämpinge report demonstrates the effectiveness of IRS in reusing 3D data from completed excavations. The report composition mechanism, structured by blocks, allowed Professor Apel to visualise and select the desired 3D models for each report block, combining the 3D views with the described features and the artefacts' localization. He selected the best perspective and zoom level to better illustrate the report description, providing the reader with the ideal viewpoint for understanding the archaeologists' field activities, reasoning, and interpretation. The report was also enriched by linking images, documents, and 3D models.

The possibility of selecting different perspective views of the 3D content to dynamically illustrate the narrative provided the reader with the ideal perspective to comprehend the archaeologist's work and reasoning. A short training session made the report writing a manageable task once the data had been set.

However, using IRS after the excavation was completed ignored the potential to exploit it in the field and thereby perform reflexivity and multivocality. For this reason, it appeared clear that the validation of this methodological approach would be valuable if carried out during ongoing excavations.

7.1.2 Experiment 2

RQ: How effective are online 3D visualization systems in supporting excavation data analysis and interpretation and contributing to a deep-learning approach to field education?

The experiment conducted at Södra Sallerup with the IVS showed that the availability of immediate 3D visualization tools supports undergraduate students in analysing and interpreting the archaeological record. Students could virtually visualise and compare multiple excavation units in the same virtual environment. They could combine the same stratigraphic unit uncovered in several excavation units at different times in a way not possible with standard documentation methods.

The experiment highlighted how the availability of detailed 3D documentation encourages field interpretation and provides significant support throughout the process. The experiment also demonstrated the impact of 3D web visualization platforms on higher education and, in particular, their ability to support students during archaeological fieldwork.

In this experiment, the questionnaires aimed at assessing the use of IVS for stratigraphical analysis and comparisons with data and illustrations from previous excavation campaigns, and to determine its ease of use in accomplishing these tasks. The results of the anonymous questionnaires completed by the students offer a positive assessment of the IVS in supporting archaeological practice and, at the same time, demonstrate the strong connection between the excavation archive and the archaeological report and emphasize the need to overcome the separation existing between them (see Figure 46).

Despite the positive results, this work revealed some significant limitations. The inability to implement the data in the field prevented the excavation team from reviewing the work carried out during the investigation and taking a reflexive approach. Furthermore, the missing connection between the 3D content and its associated information highlighted its shortcomings and suggested the need to structure the archaeological data in order to interconnect the 3D visualization components with semantics and interpretation.

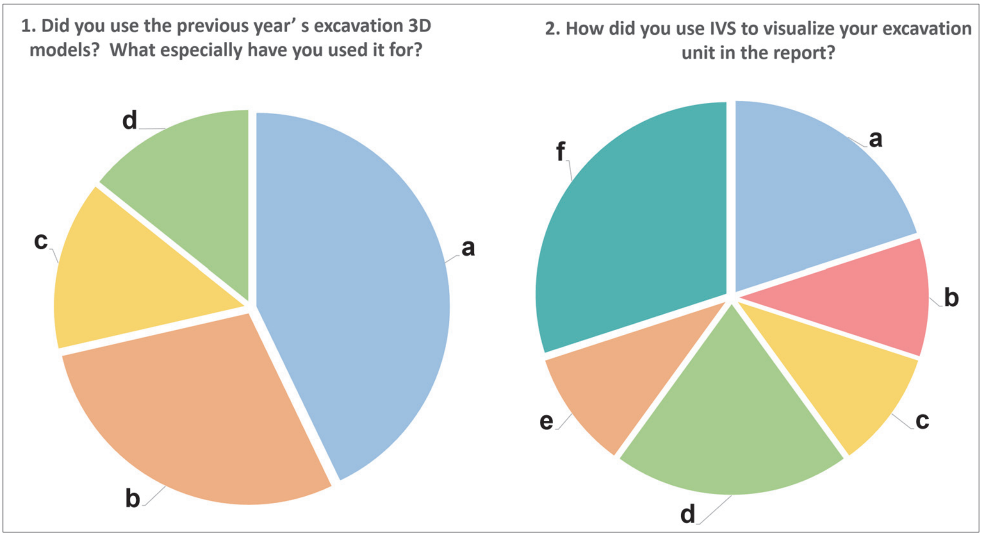


Figure 46. Questionnaire charts
The charts graphically illustrate two respondents' answers to the anonymous questionnaire. Answers to Question 1: a) to compare the characteristics of your excavation unit with those of a close one previously excavated; b) to compare the characteristics, find location and thickness of your excavation unit with those of a close one previously excavated; c) to compare the characteristics and thickness of your excavation unit with those of a close one previously excavated; d) to compare the thickness of the layer excavated in your excavation unit with that of a close one previously excavated. Answers to question 2: a) to visualize plan; b) to visualize plan and find position; c) to visualize plan, the excavation unit position in its context; d) to visualize section, find position, excavation unit position in its context; e) to visualize section, relations to other excavation units, the position of the excavation unit in its context; f) to visualize the relation to other excavation units. Image by Paola Derudas.

The data management system at the heart of the IRS and IVS was, in fact, not ideal for managing a larger and more diverse set of data. This work provided important insights into the potential impact of 3D visualization on field practice and set the direction for further implementation of the system.

Between Experiments 2 and 3 (i.e., Södra Sallerup and Västra Vång), an analysis of 10 online multimedia publishing systems designed for the presentation of archaeological data showed that these systems fail to provide access to the entire dataset of information, to incorporate tools that support reuse and interoperability, and that also implement narratives and new interpretations.

This analysis identified the characteristics needed for a platform that directly links intellectual reasoning and the data archive, allowing archaeological digital curation to be undertaken. The later work focused on achieving these goals.

7.1.3 Experiment 3

RQ: How effective is a semantic web information system as a unique tool for documentation, management, publication, and reuse of data and reports in single-context-method excavations?

Experimenting with 3D data documentation and a web-based publication system based on 3DHOP since the beginning of the research project in 2017 demonstrated the benefits of 3D visualization components in supporting archaeological practice. 3D model availability on-site using the 3D GIS supported interpretive reasoning but also highlighted the limitations of using proprietary software as it was only accessible to team members on site and required skills for advanced use.

Sharing the virtual excavation content and features with off-site colleagues by publishing online the 3D data with the IVS encouraged participatory engagement and off-site reflexivity. The recurring experimentations conducted at Västra Vång let us experiment with and evaluate new methodological approaches and tools and design solutions to improve them and address the identified shortcomings.

The design and logical model of Archaeological Interactive Report were framed to address the needs and methodology shortcomings identified in Västra Vång documentation and management. Initial experimentation with the previous campaigns' data implementation demonstrated the potential of an information system capable of housing all the information gathered over several campaigns. Using the data recorded in the online archive to build an interactive 3D-based site report that allows access and exploration of the primary data (used to build such interpretive narratives) enabled critical evaluation of the interpretation (Larsson & Löwenborg, 2020) and encouraged the use of the system as the primary tool for documentation and data management in the 2021 season.

The analysis of one of the archaeological features excavated across three campaigns, later interpreted as a posthole (Svensson & Derudas, forthcoming), was enhanced by using AIR: combining the 3D models representing it in the same 3D scene allowed the archaeologists to explore it both on-site and off-site to discuss interpretative hypotheses based on old and new information. The use of AIR, combining and exploring archaeological features with previously interpreted ones, allowed archaeologists to compare similar features previously investigated and re-interpret them.

The effective use of AIR in promoting multivocality, flexibility, and archaeological digital curation in single-context-method excavations encouraged its experimentation with more complex excavation environments such as maritime excavations. Its modular and flexible structure suggested a possible extension of AIR to incorporate data from other specialists.

7.1.4 Experiment 4

RQ: Can a semantic web information system designed for terrestrial single-context excavations effectively document, manage, and publish data and reports in maritime excavations?

The last experiment of this study, carried out in the multidisciplinary maritime archaeology project at Gribshunden, allowed IVS and AIR to be evaluated in a new excavation environment, where due to the physical constraints that affect this type of investigation, it was crucial to extend the archaeologists' time for visualising and analysing the underwater features. The 3D visualization technology of the IVS allowed for virtual navigation and interaction with the underwater features, but AIR finally allowed semantics to be connected to geometry (Drap et al., 2013). It also provided efficient management of the archaeological record and its multimedia. The ease of use and its flexible and expandable structure allow foreseeing multiple paths of use and further development in academia and for dissemination and outreach.

The experimentation with IVS allowed archaeologists to recreate virtual assemblages as they were dismantled over the various seasons and to virtually reposition the gun carriages recovered since 2002 in their find spots to observe their distribution and speculate on the use of the space on board the vessel. It is not possible to conduct lengthy dialogue while diving, and so by using the IVS, team members could critically discuss progress when back on land, and together plan the next phase of excavation by using the 3D models. Other researchers and specialists involved in the project could also access, explore, and interact with the 3D content and components of the wreck by simply using a web browser. In this way, they could take measurements, analyse customized plane sectioning, retrieve element co-ordinates, and extract orthoimages for publication. At the same time, using multiple tools for managing the excavation data added further complexities which had to be resolved.

Experimenting with AIR at Gribshunden made virtual assemblages' composition much more straightforward: the 3D content becomes the visualization media of the items registered in the online database. The database objects which have 3D media can be selected and visualised in multiple combinations. In the case of the 2022 campaign, for example, the underwater archaeologist Mikkel Thomsen, specialised in ship construction, created a virtual assemblage of all the trenches excavated during the three campaigns in order to take measurements of some of the ship's key components. This data proved very useful for research into the ship's construction.

Both the location of environmental samples taken in specific parts of the excavation trenches and the positioning of artefacts are possible in AIR, making the data visualization more complete and richer thanks to their metadata.

Furthermore, the interaction of the 3DHOP components with the Omeka S functionalities made it possible to customize their visualization according to the category. Finally, the ease of report composition using AIR demonstrates its effectiveness in building dynamic narratives that could be targeted for research, education, and dissemination.

The experimentation with multiple systems (IVS and AIR) conducted at Västra Vång (Experiment 3) and Gribshunden (Experiment 4), enabled the improvement of the technologies to meet the need of archaeologists working in the field and off-site. In the latest excavation seasons at both sites, the efficient use of AIR as a dynamic archive for hosting, querying, and visualising multiple data types and formats and the connected media (images, geographical data, and 3D models), and for writing an interactive report choosing and combining items already recorded in the database, encouraged its live use as a documentation tool in the field. The ease of use of AIR during the excavation allowed for reflexivity and multivocality and the testing of interpretive hypotheses while in the field. It also suggested the extension of its use in more challenging environments and in complex multidisciplinary projects involving specialists and researchers from different disciplines.

AIR made it possible to overcome the issue of producing fragmented and sparse data (Bauer-Clapp & Kirakosian, 2017). This was achieved by promoting a data structure that connects archaeological archives and data argumentation. Using AIR also demonstrated the effectiveness of employing advanced 3D web visualization technology to generate 3D online data management (Katsianis et al., 2021) capable of promoting discussion and advancing field practice.

The results of the evaluation conducted at the end of Experiments 3 and 4 through the anonymous questionnaires encouraged progress with the work. Specifically, 92% of the practitioners who explored AIR found the dynamic report easy to read. Users experienced easy access to information and good interaction with the content. In addition, 50% of respondents felt encouraged to explore further records related to the archaeological investigation described in the report (see Figure 47).

According to the respondents, the system provided a good picture of the activities carried out during the field investigation, with some remarks about the complexity of interacting with a few objects, such as small artefacts. This was probably due to the 3D canvas design interface, which has not yet been optimized for exploring this type of content.

Users found the 3D interaction very helpful for understanding the report. According to the responses received, this approach helped the gaining of a better knowledge of the sequence of deposits encountered during the investigation, by providing a clear picture of the excavation stratigraphy. Respondents' open-ended comments focused on the 3D interaction tools, on the ability to link text, illustrations, and 3D models, and on the system's ability to promote an intuitive presentation of the excavation results. Only 25% of respondents explored archaeological records unrelated to the report.

The assessment also aimed to look at aspects of accessibility, interaction with the 3D scenes, and system structure quality. 100% of the respondents appreciated the possibility of accessing detailed archaeological records available (only) through the system. The ability to review inaccessible features from multiple perspectives and gain a visual and detailed overview of the entire investigation area was considered particularly useful. 92% of the users highlighted the possibility of utilizing the system to reach a granular view of the information and identify tiny details.

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Figure 47. Questionnaire charts
The charts graphically illustrate some the respondents' answers to the yes-no questions. Image by Paola Derudas.

The level of FAIRness assessed using the self-assessment system available through SATIFYD showed that the platform meets the requirements set out by DANS for qualitative digital archaeological curation and open science.

Looking at each principle in detail, Findability reaches a 55% score based on the persistent identifiers of the entities, the description of all entities through a set of

Dublin Core metadata; the use of controlled vocabularies and ontologies; and the indexation of metadata and data in the web database and their display according to the latest Search Engine Optimization (SEO) practices.

Accessibility scored 75% based on the Omeka S REST API based on standard protocols: PHP, HTTP transfer protocol, and JSON-LD publication, which allows authenticated access to protect sensitive data; and all metadata availability, even if the rights to certain media change over time.

Interoperability scored 67% based on standard and open formats of most data; the online resolvable link of some data to other metadata; contextual information of datasets through reference to other datasets with persistent identifiers, the formats interoperability used, such as JSON-LD and RDF; the use of standard thesauri and vocabularies to describe metadata, that will be aligned to standard references such as GeoNames or AAT; and finally, the model alignment to standard ontologies such as CIDOC CRM and its extensions.

To ensure higher levels of FAIRness, data will be exposed in a triple store with a SPARQL Endpoint following further mappings (see Figure 42 for information on planned future mapping).

Reusability scored 55% based on information about data provenance (origin description of its origin and how it was produced); licence indication (Creative Commons by 4.0 attribution licence) to allow open data reuse; specification of the data rights owner; use of domain standard ontologies and vocabularies to facilitate the dataset reuse; and alignment to recently published best practices suggested by the ARIADNE Plus project (Katsianis & Styliaras, 2022).

7.2 Combined results

The site-specific findings of the four parallel experiments provide clear evidence of the powerful opportunities that digital tools and 3D visualization components offer to both terrestrial and maritime archaeological practice, transforming the way archaeologists engage with the material remains in terms of immediate accessibility and interactive engagement.

The possibility of conducting the experiments concurrently at diverse excavation sites allowed the technologies to be tested, adapted, and shaped to meet the practitioners' requirements. At the same time, it provided an opportunity to explore the archaeological material in ways that are not possible with standard documentation and management approaches, thereby broadening the possibility for formulating new and previously unimagined research questions.

This study made it possible to explore and critically evaluate new methodological approaches based on 3D visualization technologies using semantically oriented digital tools for the management and publication of archaeological excavation data, promoting data reuse and adherence to the FAIR principles.

Archaeological digital curation was developed and expanded in order to achieve these goals (Dallas, 2015). The results of this PhD also demonstrate that these goals can only be achieved through the design of flexible data infrastructures capable of hosting and combining datasets to promote multivocality, reflexivity, and data reuse. This work also demonstrates how the interdependence between description (archiving) and interpretation (reporting) is achieved when archaeologists start to use such platforms to gain a deeper understanding of the materials encountered during the survey (Dallas, 2015, p. 198).

The implementation of an online semantic-oriented archive encompasses all data recorded during the investigation, providing a FAIR access to the data and supporting the creation of narratives enriched with multiple media. The 3D contents do not function as simple visual components but as meaningful elements that can be recombined and used in the system to construct new hypotheses, revisit previous interpretations, and as a palimpsest to generate new data.

The experiment results demonstrate how 3D web data management systems can be used to improve the management and reporting of archaeological investigations and to critically evaluate how introducing such systems improves the performance of diverse practitioners.

The case studies show how web 3D and semantics foster reflexivity across the entire investigation and during the interpretation process and promote data FAIRness. They also demonstrate that this approach can be extended to different archaeological practices, enabling accessibility and data reuse in archaeological contexts with limited accessibility, as in the case of underwater archaeology.

This work shows that a holistic approach which combines multiple aspects (four case studies and experiments, the development and testing of three online operational systems tested with six instances of the use of the systems) is needed to operate a connection point between data, theory, methods, and practice.

The thesis also explores how these new platforms can be improved and aligned with rules and responsibilities raised in the current debate on responsible archiving regarding accessibility, transparency, and reuse. It demonstrated the significance of new digital methods based on 3D visualization and digital analytics tools to archaeological theory, methods, and practice.

The systems developed were improved and aligned to each case, but they also maintained a general structure across the case studies and experiments, strengthening them. During the study, these aspects were considered, and archival practices rooted in these principles were identified.

The results of this work contribute to the ongoing debate concerning the role of 3D visualization in support of archaeological reasoning (Dell'Unto, 2018; Dell'Unto & Landeschi, 2022; Opitz & Johnson, 2016), and remark on the need to promote a more responsible archival practice (Börjesson & Huvila, 2019; Champion & Rahaman, 2019; Huvila, 2016), rooted in FAIR principles (Wilkinson et al., 2016) and open science (Richards et al., 2021).

This study underlines the contribution of digital archaeology to archaeology (Perry & Taylor, 2018; Zubrow, 2006), and it demonstrates how the definition and implementation of platforms rooted in a dynamic definition of archaeological digital curation promote interoperability, data reuse, long-term preservation, and accessibility, keeping the processes of documentation and publication intrinsically entangled and interdependent (Dallas, 2015).

8. Conclusions and outlook

The thesis has demonstrated that engaging with 3D visualization methods and digital tools in the context of a dynamic, cross-experimental research design, including scope for mutual fertilization, provides an optimal way to critically evaluate the potential contribution of these new and emerging approaches to archaeological theory, method, and field practice.

The thesis results provide an extension of archaeological digital curation, where the connection between the (3D-enriched) data and the argumentation is achieved through the design of a flexible data infrastructure that fosters multivocality, reflexivity, and data reuse.

The holistic approach employed led to the definition of a novel model that ensures data openness and compliance with FAIR principles in the direction of open science.

However, this research has also thrown up new questions that need further investigation, and several pathways that could be explored. While tackling these future issues is beyond the scope of the current PhD, it is worth flagging what they are and how they could be addressed by follow-up research operating from three different perspectives: (1) institutional, (2) research-oriented, and (3) dissemination-driven.

1. From an institutional perspective, this research would benefit from more direct collaboration with institutions that promote open science and critical archiving. At a national level, the newly established Swedish National Infrastructure for Digital Archaeology, SweDigArch, would be the natural environment in which to develop this project. SweDigArch is a consortium of various Swedish infrastructures designed to facilitate the production of aggregated and harmonized datasets. The possibility of connecting AIR to such an extensive network would allow further adaptation of the system to include a wider variety of data.
2. From a research perspective, AIR can be expanded beyond the community of field archaeologists to accommodate information from different types of analyses and surveys. During the development of this PhD project, some tests were carried out to evaluate (in a preliminary form) the possibility of using the system to record archaeological information derived from

landscape surveys or to include the results of advanced material analyses in the system's structure.

3. From a public outreach perspective, the possibility of using the material stored in the 3D archive to support museums' activities is an important aspect to explore in the future. If further developed, AIR can help curators to facilitate exhibitions.

Despite not being directly linked with my doctoral project, I ran a preliminary test to assess the impact of 3D web visualization in support of public dissemination. This perspective has already been approached due to the need to present information about the ongoing Gribshunden project at the Kalvattenkuren temporary exhibition venue. It led to the design of a 3D-based interactive application for displaying the shipwreck site and telling stories about the ship's components and the excavation activities to the exhibition visitors. This work, carried out in collaboration with Blekinge Museum and the Visual Computing Lab at the National Research Council in Italy, was conceived around the Gribshunden excavation data reuse.

The outlines of the stories to be built and the available 3D models to combine with them were identified through preliminary conceptual work. A storyboard was employed to design the application, which needed to support Swedish and English content exploration.

Three stories were selected: the first story concerns the ship, displaying the 3D model of the whole ship and providing information on the structure, its construction and the warfare aspects, and life on-board (see Figure 48). The second story describes one of the several gun carriages recovered during the excavation: the actual state of the gun carriage, its reconstruction, and a 3D animation are displayed. The third story aims to present underwater excavations to the general public. Even though the third story is not yet complete, the platform has already been installed at Kalvattenkuren and is currently used by the exhibition visitors.

This thesis started out by acknowledging the profound significance of the "Third Scientific Revolution" which is impacting all areas of archaeological theory, method and practice. Importantly, the thesis also highlighted the transformative - yet often under-appreciated - role of new and emerging digital technologies, which are demonstrating a powerful capacity to strengthen the connectivity between fieldwork, information archiving and eventual data re-use by diverse academic and societal stakeholders. The thesis advances this digital research agenda, generating insights into promising areas of future innovation and improved research practice, but also highlighting the deeper importance of anchoring advances into strong and shared ethical frameworks, not least, a proactive commitment to the FAIR principles. With these foundations in place, it is clear that the most revolutionary advances in digital archaeology still await us, and it is hoped that this thesis has gone at least some way in exploring and evaluating some of these exciting future potentials.

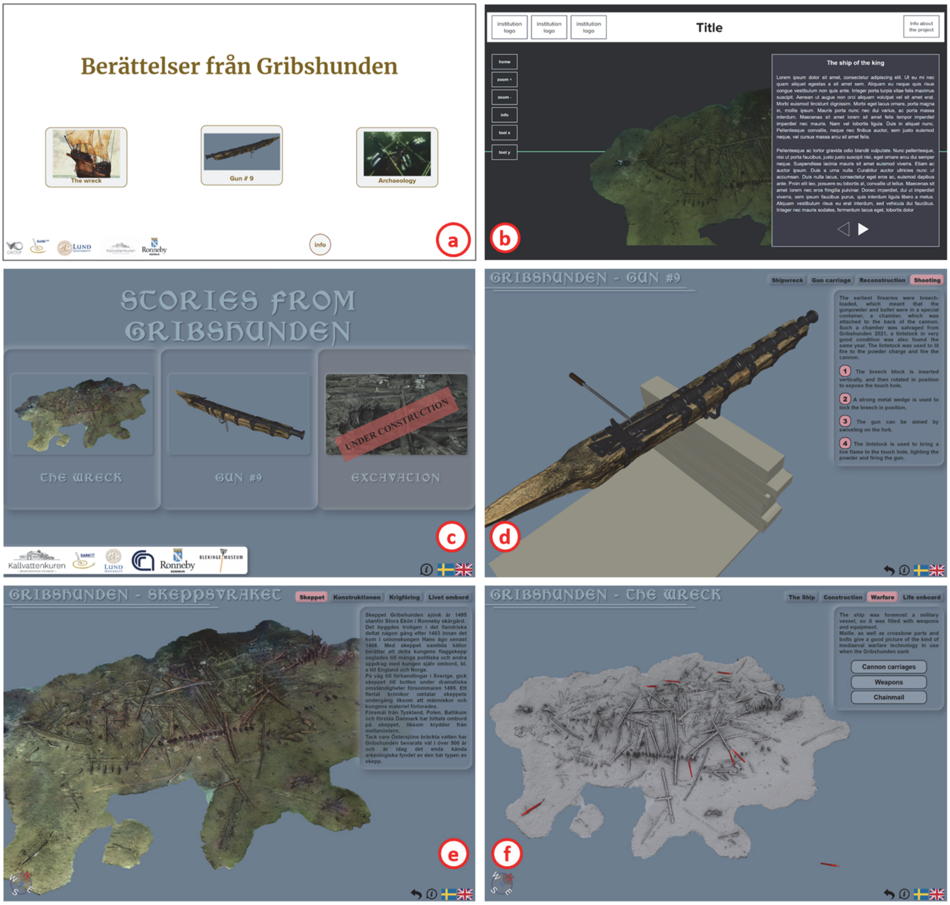

Figure 48. Stories from Gribshunden

Stories from Gribshunden: the storyboard (a, b); the homepage of the platform (c); animation of the cannon reconstruction (d); the first story on the ship structure (e); and the cannons distribution (f). Image by Paola Derudas.

9. Sammanfattning

Digitala teknologier påverkar idag oss alla och förändrar ständigt hur vi lever våra liv. Användandet av smarta telefoner och surfplattor är vardag och AI-teknologi får ett allt större inflytande på många av de hjälpmedel som vi använder för att göra livet lättare och mer effektivt.

Denna avhandling behandlar digitala teknologier och hur dessa har revolutionerat arkeologin som ämne och praktik. Tillämpningen av 3D-modeller för att reproducera såväl artefakter som arkeologiska platser och kulturmiljöer har förändrat arkeologers möjlighet att interagera med sina studie-objekt och även förlängt den tid som arkeologer har tillbuds för att hantera lämningar innan de slutligen förstörs genom arkeologisk undersökning. Som ett led i detta har arkeologer börjat använda 3D-modeller mer eller mindre regelmässigt vid arkeologiska undersökningar för att understödja såväl dokumentation som analys. Detta har även möjliggjort virtuella tillbakablickar till arkeologiska platser som undersökts sedan tidigare för att pröva och utvärdera tolkningar och hypoteser. Därutöver har ökad spridning och tillgängliggörande av plattformar för delning av 3D-modeller, exempelvis Sketchfab, skapat möjligheten att organiserat samla och katalogisera stora mängder av denna typ av arkeologisk information.

Arkeologi är idag en mångvetenskaplig och tvärvetenskaplig disciplin, vilket ställer ökade krav på möjligheten att tillgängliggöra arkeologisk data, såsom 3D-modeller, till en stor mängd specialister och arkeologer inom och mellan olika forskningsprojekt. Därmed är det högst angeläget att utveckla, applicera, utvärdera och beforska system som möter dessa behov och utmaningar.

Det framgår tydligt att den så kallade tredje vetenskapliga revolutionen inom arkeologin såhär långt inte gjort något större avtryck på utformningen av en av den arkeologiska undersökningens mest primära dokument – undersökningsrapporten. Dessa rapporter är ofta den enda slutligt kvarvarande produkten efter att en arkeologisk lokal har undersökts och därmed ofrånkomligen destruerats. För många arkeologiska projekt utgör undersökningsrapporten den enda kontaktytan mot intressenter utanför arkeologin. En kontaktyta som sällan utnyttjas utöver de krav som kulturminneslagens paragrafer ställer gentemot arkeologins aktörer och samhället i stort. Den data som utgör rapportens källmaterial, såväl fysiskt som digitalt eller immateriellt, arkiveras i museernas magasin samt i nationella arkiv. En syntes av källmaterial och tolkningar är främst åtkomlig genom undersökningsrapporten, vilken i sin digitala form endast tillgängliggörs som en pdf-fil, med mycket begränsad sök- och användarbarhet.

Med anledning av det stora och ökande behovet av tillgänglighet och visualisering av undersökningsdata inom arkeologisk praktik och forskning utforskar denna avhandling nya digitala format för rapportering och syntetisering av arkeologiska undersökningar. Genom att utöka rapportframställningen med 3D-modeller, vilka är direkt länkade till undersökningens data, skapas en lättarbetad överblick och en sökbar helhetsmiljö inom vilken det mångfacetterade källmaterialet effektivt kan analyseras och presenteras. Metoden har utvecklats och utvärderats under fyra och ett halvt års tid genom undersökningar av fyra olika arkeologiska platser, utvalda som fallstudier. Platserna och fallstudierna har valts utifrån sina skiftande kronologiska, metodiska och kulturhistoriska karaktärer för att ge såväl bredd som teoretisk och metodisk grund till studien som helhet. Fallstudierna speglar på så vis ett brett spektrum av arkeologisk forskning och praktik – från marin- till land-arkeologi och från mesolitikum till sen medeltid. Samtliga fallstudier har dokumenterats, analyserats och presenterats, såväl inom forskningsfältet som för intresserad allmänhet, med hjälp av samma integrerade system, med 3D-baserad tillgänglig digital teknik som grund.

Tre olika web-baserade plattformar för visualisering av och interaktion med 3D-baserade arkeologiska data och narrativ har utformats och utvärderats genom de nämnda fallstudierna. Avhandlingens fallstudier genomfördes i följd. I och med detta tillvägagångssätt kunde såväl potentialer som utmaningar identifieras och förbättras genom studien som helhet. Detta skapade likaså möjligheter att analysera verktygens effektivitet och tillgänglighet för aktörer med skiftande behov och verksamma i helt olika miljöer, såväl inom som utom de arkeologiska disciplinerna.

Avhandlingen har resulterat i fem vetenskapliga artiklar, tre web-baserade plattformar och sex applikationer av desamma för att publicera, analysera, förmedla och tillgängliggöra arkeologisk data från fallstudiernas fyra undersökningslokaler. Fyra av artiklarna behandlar de olika fallstudierna och analyserar dessa utifrån aktuella forskningsfrågor. Den femte artikeln består av en utvärderande analys av de för närvarande tillgängliga plattformar som används för att publicera och tillgängliggöra kulturmiljöer och arkeologiska data. Denna artikel identifierar på så vis aktuella utmaningar och problem som bemöts genom fallstudiernas utformning.

Avhandlingen belyser den transformativa utveckling som just nu pågår inom arkeologisk forskning och praktik rörande digitala verktygs fundamentala roll avseende dokumentation, analys, syntetisering, tolkning och förmedling. Den argumenterar för en mer långtgående integrering av 3D-teknik inom arkeologiska fältundersökningar genom att till fullo utnyttja web-baserade plattformars potential för att berika analys och narrativ.

De nya och innovativa metoder som utvecklats, applicerats och utvärderats i denna avhandling visar likaså hur den pågående digitala revolutionen inom arkeologisk forskning och praktik även kan understödja etiska och samhälleliga dimensioner av hur arkeologiskt källmaterial och tolkningar behandlas, arkiveras och förmedlas. Avhandlingen visar på potentialen för den data som arkeologisk forskning producerar att i framtiden brukas enligt FAIR-principen. Alltså, att med hjälp av reflexiva och integrerande metoder och system bli – Findable, Accessible, Interoperable, och Reusable.

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