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Black Sea Wreck Virtual Reconstruction to Reinvigorate Archaeological Data and Comparative Studies

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Abstract
This short report tests a repeatable methodology for creating detailed virtual reconstructions where the model is a scientific container of the reconstruction information.

The project reconstructed a Black Sea shipwreck using a photogrammetry survey and proposed a hypothesis of how it would have looked prior to sinking. To this "shell", the metadata and paradata were added using BIM: Extended Matrix and Graphic Scale of Evidence.

Academically, the "source-based reconstruction" opened a new spectrum of questions related to the ship and its community (chronology, building, propulsion, usage). The models also reported potential as public engagement tools, displaying the scientific background of archaeology.

Key words:
Black Sea MAP project, Virtual Source-based Reconstructions, Archaeology, Extended Matrix [EM], Graphic Scale of Evidence [GS], Reconstructive Units [RU].

Introduction

Advances in digital technology coupled with increasing usage of computers and data-management since the mid-20th century have revolutionised methods of communication and information transportation (Schoenherr, 2004). Many disciplines made advances during this period thanks to the possibility of newer, more powerful computers to process big blocks of data, and especially by using the third-dimension (3D) to record and present hypotheses, prototypes, assets in engineering (Remondino and El-Hakim, 2006; Pantoja, 2014; Avila-Roldan, 2015), biology (Lavy *et al.,* 2015), and museology (Allard *et al.,* 2005; I Juan, 2010; Antlej *et al.,* 2011; Robles and Garcia, 2015).

Likewise, archaeology has widely benefited from the expansion of the digital world. It is possible to trace archaeological underwater photogrammetry back to the 1970s (Pacheco-Ruiz *et al.,* 2018: 120). Even though not all archaeological teams use scanners and photogrammetry to develop their aims, digital tools and reality-based 3D models have benefits at all stages of an archaeological project, including survey (Calder *et al.,* 2007), recording (McCarthy *et al.,* 2019*)*, data analysis (van Ruymbeke *et al.,* 2008; von Schwerin *et al.,* 2013), and even for public engagement and museums (Hawkey, 2004; Nebel *et al.,* 2020).

Currently, the largest application of these technologies is for recording extant remains and developing what is known as reality-based models or digital twins. Conversely, the potential of these digital technologies for displaying and testing interpretations and hypotheses (*i.e.,* virtual reconstructions), has had a different developmental trajectory (**Table 1**).

Historic reconstructions expanded quickly due to their value in presenting history in an attractive and visual manner for schools, museums, and entertainment. However, many of them are still being done by graphic designers aiming to create attractive content (Tietzsch-Tyler, 2009: 6-7, 29) (**Fig.1**). The low percentage of models being created by heritage professionals is mainly due to difficulties with resolution, scientific reliability, and costs. However, as digital tools developed and became more affordable towards the end of the last century, the potential pushed for the foundation of two new archaeological subdisciplines specialised in promoting the value of digital models for historic and archaeological purposes: Virtual Archaeology (VA) and Cyber-Archaeology (CA). These subdisciplines aim beyond reality-based models to digitally construct an interpretation, in 2D or 3D, of the archaeological assets at some point in time prior to their decomposition. The official definition for these virtual reconstructions:

"*[…] involves using a virtual model to visually recover a building or object made by humans at a given moment in the past from available physical evidence of these buildings or objects, scientifically reasonable comparative inferences and in general all studies carried out by archaeologists and other experts in relation to archaeological and historical science*." (IFVA, 2012: 3).

Nevertheless, the expansion of virtual reconstructions demonstrated the lack of methods for recording the reconstruction processes and the sources used for them. This limits the possibilities of scientifically validating 3D models, which could be shared and reused to aid other projects. Therefore, a series of researchers developed different methods to standardise the recording of the sources used in the reconstructions (metadata) and the chain of thoughts and processes needed to convert the source into useful information for the reconstruction (paradata). These "completed" models have been named as research-led or source-based models (Demetrescu, 2018).

This article focuses on this gap in research by promoting the value of well-documented, scientific, and source-based virtual reconstructions to advancing maritime archaeological research, namely through the creation of a source-based virtual reconstruction of the Southstream_2014_abs_add_BS_2010 shipwreck from the Black Sea MAP project.

Aims and objectives.

The main aim of this research has been to promote source-based models or research-led models as scientific tools and test their efficiency and application towards facilitating international and collaborative archaeological research. Questions that have motived this research include the following:

1. What are the benefits of having a detailed record of hard-to-access archaeological sites, such as the Black Sea wreck used as this case study?
2. Can the methodology be adapted to the peculiarities of a maritime site and, in this case, underwater?
3. Can visual metadata encourage the reading and re-use of the results?

The high methodological content of the project made it necessary to reaffirm the value of the proposed reconstructions to prove that they are not a simple "extra attractive step", but rather a useful tool to aid archaeological research, and in this instance, the case study of the Black Sea MAP wreck. Further questions include the following:

1. Is it possible to achieve greater understanding on the studied wreck (e.g., chronology, construction, function) through its sourced reconstruction?
2. Can the standardised methodology help increase knowledge of maritime archaeology by promoting in-depth analysis and comparative studies?
3. Can the reconstruction of this wreck become a detailed archive? Is this more useful than the reality-survey model (photogrammetry)?
4. Can the reconstructions of the wreck become valuable assets for museums and public engagement?

The site: Southstream_2014_abs_add_BS_2010

The Southstream_2014_abs_add_BS_2010 wreck was found during the Black Sea Maritime Archaeology Project (Black Sea MAP), which took place between 2015 and 2019 with the purpose of surveying 2000 km^2 of the Bulgarian Exclusive Economic Zone (EES) through geological core sampling and geophysical survey (Pacheco-Ruiz *et al.,* 2018; Pacheco-Ruiz *et al.,* 2019) (**Fig.2**).

The archaeological potential of the Black Sea relies on the high preservation ratio of its remains. The low oxygen-levels present below *c.*150 m depth means that the remains under that level are kept in anoxic conditions, which are ideal for organic material preservation.

The aim was to reconstruct in high resolution the palaeoenvironment of the Bulgarian shelf to learn about the impact of environmental changes during the Late Pleistocene and Holocene on the human population of the area (Pacheco-Ruiz *et al.,* 2019: 1). This would help establish the history and development of the prehistoric communities that grew to become complex societies and, later, historical cultures (Pacheco-Ruiz *et al.,* 2019: 2). A subsidiary result of this survey was the location of 65 shipwrecks by 2017, between 40 and 2,200 m deep and dating from the 4th century BC to the 19th century AD (Pacheco-Ruiz *et al.,* 2019: 2).

The survey data was acquired using remotely operated vehicles (ROVs) that had geophysical and recording equipment (HD cameras, acoustic bathymetry, laser, side-scan and seismic). These vehicles were launched from a DP2-rated Multi-Purpose Support Vessel, which are usually for high precision offshore surveys.

The wreck studied in this research was the Southstream_2014_Abs_add_BS_2010, found on 16 September 2017, at a depth of 2,070 m below contemporary Black Sea mean sea level (BSMSL)

(**Fig.3**). It was recorded by a WROV HD Shilling Robotics equipped with HD cameras. Nevertheless, neither excavation nor geophysical studies took place due to the depth of the remains.

The limited access to the site and the lack of excavation made it an ideal case for this research project to test how much more data can be gained by using source-based virtual reconstructions.

Methodology

Principles of the methodology

Computer-based visualizations have already been defended as scientific tools in official documents such as the London Charter and the Seville Principles. These aimed to protocol the increasingly expanded field of VA, writing a series of principles to maintain the scientific base of virtual products as opposite to entertainment visualisations.

The London Charter (2006, reviewed in 2009) was oriented toward computer-based visualisations of cultural heritage. It promotes the creation of scientific, accurate, and accessible graphic representation of cultural heritage through the application of new technologies, targeting different audiences (academia and the general public) (Denard, 2009: 8-9). The six principles of the Charter are: implementation, aims and methods, research sources, documentation, sustainability, and access (Denard, 2012). This project focused on one of these principles: documentation. The London Charter explains that the documentation of a project should permit repetition of the process, for reuse and understanding of the method and results by any audience to which it will be presented, including specialists and non-specialists (Denard, 2012: 66-68). Therefore, it encourages the publication of the metadata and paradata behind the reconstructions, but does not specify how or to what level of detail.

The second official document focused more on the archaeological discipline: the Seville Principles of 2011-2012 (IFVA, 2012). One of the main contributions was the definition of the most commonly used terms. Among them, it was decided to use the term of VA to embrace the use of digital technologies in archaeology:

"*The scientific discipline that seeks to research and develop ways of using computer-based visualisation for the comprehensive management [inventories, surveys, excavation work, documentation, research, maintenance, conservation, preservation, restoration, interpretation, presentation, access and public use of the material remains of the past] of archaeological heritage [i.e., tangible assets].*" (IFVA, 2012:3).

The eight principles collected in this document are interdisciplinarity, purpose, complementarity, authenticity, historical rigour, efficiency, scientific transparency, and training and evaluation. The two principles reinforced through this project are authenticity, highlighting the importance of reflecting the levels of reliability of the models, and scientific transparency, claiming that computer-based visualisations must be verifiable in order to promote VA as a scientific discipline.

These three principles explained above are the main focus of the methodology of this study, and, therefore, the core of the standardisation methods used.

Standardisation methods

Standardisation methods for virtual reconstructions have been promoted since the introduction of the above Charters; however, their usage has been limited among the scientific community. A study done two years after the Seville Principles evaluated 686 publications for the usage of technologies in heritage, of which 27% were focused on virtual reconstructions and only 1% of the latter included the creation of metadata in their project as a validation tool for their hypothesis (Cerato and Pescarin, 2013). This low percentage "*contributes to a widely diffuse perception of the virtual reconstruction as an 'aesthetic' endeavour more than a scientific tool*" (Demetrescu, 2018: 102).

There have been different attempts to create common standards for VA reconstructions. This project combines three different approaches due to their reciprocity and compatibility. They have all been used before, achieving beneficial outcomes for documenting the reconstructive models (**Table 2**). Therefore, their combination could result in a more accurate, detailed, and accessible form of recording metadata and paradata to create comparable and re-usable scientific outcomes.

Extended Matrix (EM)

The Extended Matrix (EM) language and methodology is the main base of the standardisation done for this project. The tool was created by Demetrescu (2015), who defined it as "*a visual node-based formal language grounded on a stratigraphic approach designed for virtual archaeology and on the theory of knowledge graphs*" (Demetrescu and Ferdani, 2021: 2). Its development is still ongoing, mainly at the Virtual Heritage Lab of the CNR ISPC in Rome, Italy (Demetrescu *et al.,* 2016; Demetrescu and Fanini, 2017; Fanini and Demetrescu, 2019; Demetrescu, 2020, 2021; Demetrescu and Ferdani, 2021).

Using semantic tools that already exist for recording reality-based models and the stratigraphic principles of the Harris Matrix, Demetrescu proposed a new formal node-based language to document the particularities of archaeological 3D virtual reconstructions.

The language is based on two types of nodes: metadata and paradata. Metadata nodes record the elements present, including the remains recorded through the Harris Matrix and the “lost” elements represented through newly designed nodes that visually display the levels of reliability of each hypothesised element. The paradata nodes represent the chain of processes and thoughts that were developed to create the metadata nodes from the sources (**Fig.4**). The combination of these types of nodes creates a string of the EM (**Fig.5**), which solves the issues of “Black Box Effect” and “Palimpsest Effect” usually found in archaeological projects.

Furthermore, thanks to a plug-in to a 3D modelling software, it is possible to join the EM graph to the visual representation of the virtual reconstruction, making it easy to access the information. Therefore, the EM language connects the present field archaeology with its lab reconstruction and allows for tracing and re-evaluating each step of the reconstruction, which promotes the above-mentioned principles. It defends international scientific reconstructions through the recording and publication of transparent and verifiable results that could show the complexity and multidimensional aspect of the archaeological hypothesis (Demetrescu and Ferdani, 2021: 1) (**Fig.6**).

Reconstructive Units (RU)

The Reconstructive Units (RU) are context sheets proposed to document and help publish the metadata and paradata of virtual reconstructions (Molina-Vidal and Muñoz-Ojeda, 2015).

The proposal suggests creating scientific repositories that record the documentation of each model through an easy and accessible standard context sheet (**Fig.7**). The forms will summarise complex ideas in a concise and integral manner to ease the processes of creation, publication, and access to the information about the reconstruction.

The template proposed uses drop-down menus to limit the options available, mixed with other fields of free writing to describe the arguments and hypotheses developed (Molina-Vidal and Muñoz-Ojeda, 2015: 3-4). It aims to establish a standard and common semantic for this type of metadata.

Graphic Scale of Historic-Archaeological Evidence (GS)

Different graphic scales have been proposed over the years, which attempt to visually condense complex ideas. In this case, the Graphic Scale of Historic-Archaeological Evidence (GS) is focused on promoting data granularity, model authenticity, and reliability of the sources of an archaeological virtual reconstruction (Aparicio-Resco and Figueiredo, 2016). This scale was first designed by Clifford, Kostenec, and Berger to display the degree of historic-archaeological evidence of the reconstructions developed during the project "Byzantium 1200" (Ihsan-Tunay and Berger, 1994 - http://www.byzantium1200.com/).

The current most popular version was published by Aparicio-Resco and Figueiredo (2016), which aimed to eliminate the "Black Box" effect. It uses different fixed colours to represent the degrees of evidence that supports each found or reconstructed unit of the model: cold colours represent low levels of authenticity, while warm colours show higher reliability (**Fig.8**).

The assignment of each colour is, at a certain level, still subjective and dependent on the team members of the reconstruction project. However, this tool still drastically increases the principle of transparency inside Virtual Archaeology projects.

Furthermore, it has benefits beyond research, acting as a new innovative tool for public engagement thanks to its capacity to display in a simple manner the reliability of the model to diverse audiences with different levels of knowledge.

Application of the methodology

The methodology used in this project drew from the process of creating an EM (Demetrescu and Ferdani, 2021). In general terms, its components can be seen as:

1. Data collection: documentation and reality-based model
2. Data management and sourcing
3. Hypothesis and cross-referencing: Standardisation methods
4. Reality model
5. Publication and public engagement

Data collection

In order to create a source-based model using the methodology proposed, it is important to have three types of information:

1. A reality-based model to use as a base.
2. A graph of the units found on the site (*i.e.,* in archaeological excavation this is normally represented using the Harris Matrix)
3. Ideally, reports and documentation of the stratigraphic units and environment of the site to help with the understanding of the remains and reconstruction.

The data provided by the MAP team to be used as base for this study was

a. A record of all the shipwrecks found during the Black Sea MAP
b. UHD video recording of the site
c. Survey data of the site
d. Survey photographs of the site that allows to create a photogrammetry model of it
e. Processed photogrammetry model of the site
f. LiDAR point cloud data of the site
g. Comparative data from two other sites found during the Black Sea MAP that present similar remains.

Therefore, from the base data required, it was possible to fill the reality-based model using a photogrammetry model of the site (**Fig.9**). On the other hand, there have been no further works done on site apart from the visual survey of the remains, hence there are no specific publications regarding the interpretation of the remains. In addition, the lack of excavation means that no Harris Matrix has been done for the site, nor any other type of reading of the remains.

Data Management and Sourcing

The data management stage is meant to create any type of base information that was not possible to acquire from the field project. In this case, it refers to a graphic representation of the remains to be able to build the reconstruction over it (specifically the Extended Matrix). Since there was no stratigraphic data, and it was not possible to build it from just the pictures, it was decided to create a graphic scheme based on the construction sequence interpreted from the remains, explaining the current relationships between them (**Fig.10**).

At this level, once all the base data was covered, an initial search for sourcing was done by creating an Excel file to manage them correctly. This document acts as a "Dossier Comparative" summarising possible source, general knowledge of construction, and comparative studies that could help interpret the remains, *i.e.,* the metadata and paradata of the model (**Fig.11**) (Demetrescu, 2021: 11). Therefore, this document acted as the basis for creating a reconstructive hypothesis and also allowed for consultation during the reconstructive process with supervisors and the Black Sea MAP team.

The first source used is the photogrammetry model of Southstream_2014_Abs_add_BS_2010 wreck. From it, and thanks to the guidance of Dr. J. Whitewright, it was possible to identify primary comparative elements among the remains: longitudinal crossbeams, frame spacing, number, and placing of the crossbeams. This helped to identify other sources when looking for comparative wrecks with similar accessibility and chronology. The two main comparisons for the reconstruction have been other Roman shipwrecks found during the Black Sea MAP survey: Southstream_2014_Abs_068, whose bow was remotely cleaned to show the features (personal communication, F. Petrotti) and Southstream_2014_Abs_014. Conversely, the Tantura, Dor, and Ma'agan Michael wrecks were also examined to determine if the remains could have been from later periods.

Hypothesis and Cross-referencing

The third level of the proposed methodology should start as soon as possible and parallel to the creation of the "Dossier Comparatif". The creation of the volumes of the hypothesised wreck will act as a guide for the reconstruction and point towards modifications and changes needed during the creation of the hypothesis that would not have been visible when theorising about it.

The modelling was done using FLOS software, Instant Meshes and Blender 2.9.

In conjunction with the modelling, it was fundamental to start recording the metadata and paradata of the processes, as the evidence of why the elements were constructed in that manner was fresh, making it easier to write. Moreover, it was more bearable to write the metadata and paradata immediately rather than having to build it all quickly at the end.

The first technique used was the recording of a RU for each element in the virtual model (**Fig.12**). This allowed setting its reliability colour for use when texturing with the GS. These RUs also include details such as texture, material, height, length, and so on.

The second technique was the construction of the Extended Matrix of the reconstruction. One metadata node was created per RU, using the same name, and one paradata node was created per source recorded on the "Dossier Comparatif". Each node was given a description of what it represents. With the support of the other paradata nodes, it was possible to build different strings of the EM connecting the content (metadata node) with its sources (paradata node). Once the whole EM was constructed, it was linked to the virtual representation using the EM tools from Blender 2.9. This model is called a "Proxy" and contains all the metadata and paradata information, promoting the principle of transparency (**Fig.13**).

The last technique, the GS, was already recorded on the RU, so the only thing left was to texture the 3D model using the fixed colours of the GS (**Fig.14**).

This exhaustive recording of the reconstructive process has been useful to accommodate any necessary modifications of the processes, and to allow sharing and discussing the hypothesis with specialists and supervisors in a straightforward and open manner. The techniques have also proven to be easy and accessible, allowing for a multidisciplinary team to remain in communication through the metadata of the project.

Reality Model

This is when the archaeological hypothesis becomes “attractive”. The raw model was textured using the interpretation and details recorded in the standardisation techniques and placed in an environment. The aim is to achieve a photorealistic look without losing historical integrity (**Fig.15**).

This stage shows again how efficient it is to use the standardisation techniques during the previous step, greatly reducing the texturization process. This even allows the model to be sent to a graphic designer for the creation of a photorealistic finish, since all the core historical data needed would have been already decided and linked to the model through the metadata.

Publication and Public Engagement

This last step is fundamental for the discipline, since data that is not shared with the community or the public does not fulfil the aim of the archaeological discipline of building historical knowledge to be used by the society.

Academically, the aim of the work was to show the interpretation process developed over the course of the project and share, as much as possible, a reusable model. With this in mind, a series of source-based models (proxy and textures) were made (**Fig.16**), together with a report of the reconstruction process, including the metadata and paradata, and the overall results achieved (Cristina-Gonzalez, 2021).

From an engagement point of view, the objective was to create visually attractive, engaging, and interactive models that were at the same time historically accurate and informative. The two main outcomes were: (1) a virtual tour for visitors using ThingLink with short informative click-on panels about the wreck, the Black Sea MAP project, and the reconstruction process (**Fig.17**); and (2) a display of 3D replicas of the recorded remains and the hypothesis, showing the process and reliability levels of historical reconstructions (**Fig.18**).

Results and Discussion

The results achieved in this project could be seen in two different ways: archaeological potential and the efficiency of the method used to create international source-based models.

Archaeology Viewpoint

Firstly, and as explained above, the creation of a source-based model of the Southstream_2014_Abs_add_BS_2010 wreck produced a series of outcomes for both the academic community and the general public. Secondly, and more importantly, this source-based model also helped promote a greater understanding of the remains. Four main areas were identified (**Fig.19**). The best-conserved planking is on the port side, close to the bow. It is possible to see two sets of planking, the right one clearly being the outer planking of the hulk. This latter section holds in place three to four strakes of planking without the presence of any frames, suggesting some kind of juncture between the planks. Furthermore, the shape of the bow planks from the photogrammetry suggests the presence of a ram-like bow, a known feature of Roman merchant ships.

Regarding the frames, they all present a rectangular shape of *c.* 20x10 cm and a spacing of 70-88 cm. In addition, the photogrammetry shows that the structure has collapsed on the right side, widening the shape of the original ship. This, together with the rudder found on the aft side, could suggest the existence of a "wing-like" planking or rudder housing.

Thanks to the support of Dr. Whitewright, it was possible to identify two longitudinal cross beams as part of the internal structure. These were placed over the top deck on Roman merchant ships as a middle structure of the cargo holds. Meanwhile, it was a Byzantine tradition to place them next to the keel, as keel sisters. Nevertheless, the presence of thick timbers diagonal to the longitudinal beams suggest that the latter were not at the skeleton level, but rather part of a possible middle platform between top decks and around the mast.

Finally, no oars were found among the remains, suggesting that the sail was the main propulsion of the ship, specifically, a main square sail and a bowsprit popular in Roman constructions. A detailed study of the rudder remains helped support the hypothesis of a V-shaped rudder system.

The final reading of the remains (**Fig.20**) is what gave base to the proposed reconstruction. It is true that this is one single vessel, and this project could represent a starting point to create a series of comparable in-depth source-based virtual reconstructions and research, which could push for a better understanding of "*technological development, trade, warfare and strategies of competition and control that punctuated the cycles of human affairs*" (Pacheco-Ruiz *et al.,* 2019: 12).

Method Viewpoint

Secondly, this study also tested the efficiency and utility of creating source-based models from maritime archaeological assets. This was possible due to the experience of constructing the models, but also thanks to an anonymous and online survey developed for both professional archaeologists and the general public.

The academic survey (**Fig.21**) contained a quick explanation of the standardisation techniques. Our of 160 answers, a third of the respondents voted that a combination of three methods would achieve the most detailed record, while another third preferred to use just the EM. Ninety-five percent defended their usefulness to reuse data and create attractive outcomes, whereas 5% said they seem too difficult to understand and were not worth creating. Similarly, 95% voted that the information they presented could be very useful and report benefits beyond "traditional" methods, while5% affirmed that the complexity of the techniques obscures any improvement in relation to "traditional" methods. Two thirds of the participants agreed on the scientific level and validation of these models. They would be interested in learning the techniques, half of which estimated that it would take a long time to learn but could be interested in adopting them for their projects. Meanwhile, the other third voted that the techniques are too complicated, and some even reported that they would not be interested in publishing or releasing metadata and paradata from their projects.

On the other hand, in the public engagement questionnaire (**Fig.22**), 99% were interested in knowing the origin of the reasoning behind the interpretations displayed in museums and liked how the GS models could help improve that aspect of an exhibition.

It is acknowledged that the participants of the survey (a total of 376 people) represent a very low percentage of the general group of museum visitors and archaeology researchers. However, these answers helped to obtain feedback and better understand the strengths and weaknesses of the proposed methodology and its outcomes.

The top benefit highlighted during this project was the efficiency of source-based models. Once the field data is collected and the hypothesis is set, it was quick and simple to introduce the standardised information. Therefore, this methodology shows great potential as a new step for archaeological projects. The interpretation becomes accessible and understandable for anyone that has the source-based model, and its unit-based modelling system allows quick modifications since it is possible to change one single element and its related documentation (*e.g.,* height of the mast) without needing to start again.

Nevertheless, as always, the process also encountered some difficulties. The novelty of the topic made it difficult to obtain comparable data that was correctly sourced to provide the necessary details to be used as metadata of Southstream_2014_Abs_add_BS_2010 wreck reconstruction. In addition, the experience on this model showed that the initial lack of versatility of the process (each step had to be finished to continue to the next one) did not fit with reality. The process could therefore be simplified and should be more understanding of changes and new interpretations, which are common in archaeology.

Future possibilities

The incipient character of this discipline and methodology open the door to future possibilities. Nevertheless, it is fundamental to keep testing the methodology in other case studies. The model had good results for reconstructing a wreck, even unexcavated, but it would be useful to use different base data, characteristics, assets, and periods to check the range of possibilities of creating source-based models.

Another interesting idea would be to check the accessibility of the GS in public engagement scenarios, adapting the colours, number of levels, etc., to fit different audiences.

Finally, the most significant improvement of this project would be to merge the techniques. The compatibility of the techniques means that certain areas overlap, which opens doors to finding a method that merges them in a simple, user-friendly manner.

Conclusions

To conclude, the value of source-based models was reinforced in this study for both research and public engagement purposes.

The result has supported an interpretation of the date, function, and construction. The wreck was probably constructed between the 2nd and 4th century AD for mercantile purposes. It was a shell-first construction fastened with mortise and tenons, around 34-35 m long and 12.5 m wide. The middle section of the hull was reserved for the cargo, covered with a cloth to protect it. This cloth would have gone over the diagonal crossbeams, which were held between the longitudinal beams and the sides of the ship. It was propelled using square sails and steered thanks to the two quarter rudders, accessible through the “wing-like” planking. The middle narrow deck between the longitudinal beams connected the stern and bow decks for the crew and the person in charge of the rudders.

Therefore, reconstruction models can be validated scientifically and repeated thanks to the recording of their sources (metadata) and chain of thoughts (paradata) that developed the hypothesis. The wide range of base data possible to start the method has enabled the reconstruction of a maritime archaeological asset (a shipwreck) despite all limitations (unexcavated, undocumented). Furthermore, the survey has shown that the visual approach to metadata recording makes the creation, reading, and reuse of this information more attractive to both academics and the public.

This study proposed source-base models as a new baseline to start rejuvenating archaeological documentation and bring it into the increasingly virtual world. This method is a new way of making archaeological assets accessible, comparable, and contrastable, thanks to the combination of the qualities of each standardisation technique: the visual simplicity of the GS, the schematic complexity of the EM, and the detail and organisation of the RU.

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Figures and captions

Figure 1: Reconstruction of a Roman harbour presented at the ARQUA Museum in Spain. It is based on archaeological research and has the purpose of teaching the visitors the history of Roman maritime trade; likewise, the visual attractiveness is important to catch the visitors' attention. (Photo: C. Gonzalez-Esteban)

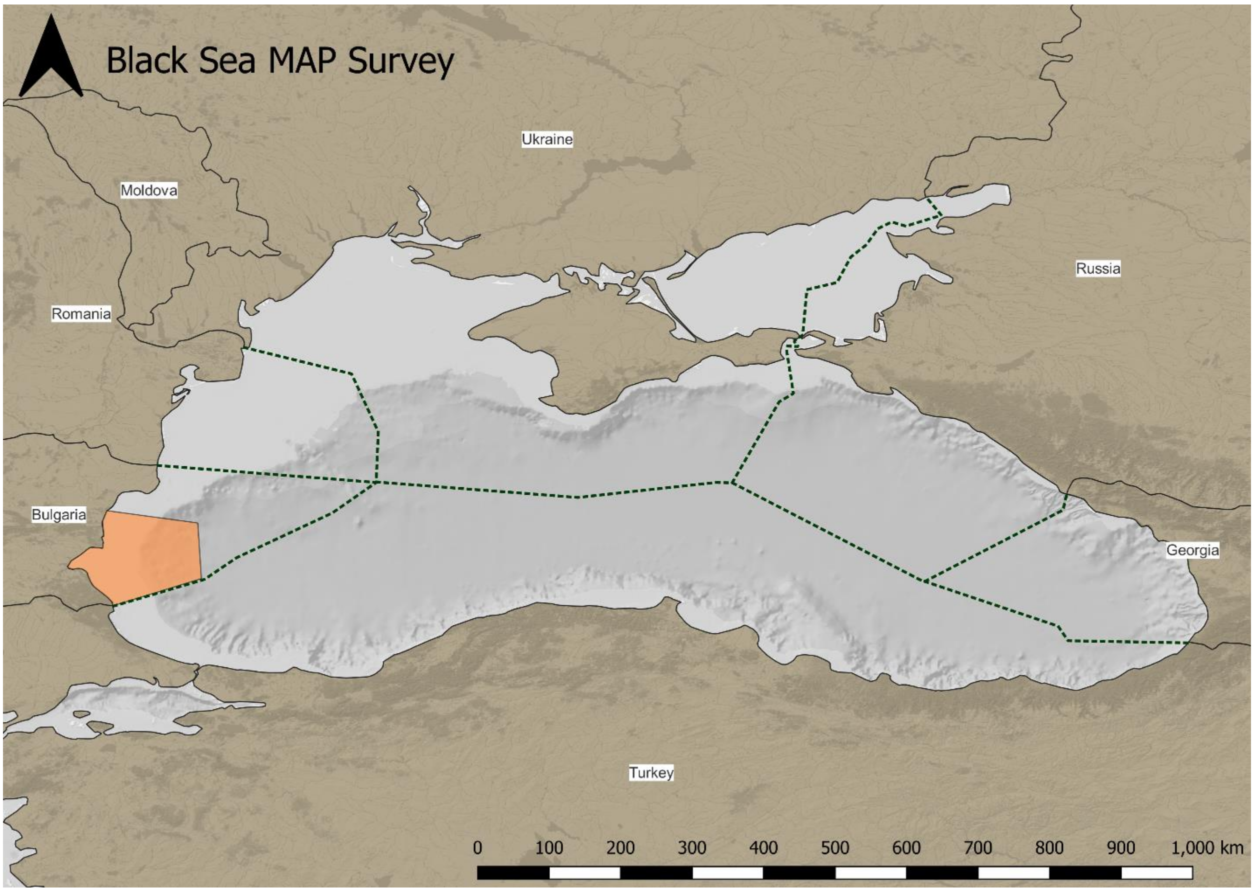

Figure 2: Map of the Black Sea. The area coloured in orange was surveyed during the Black Sea MAP Project led by the University of Southampton. The black dotted line separates the EEZ of each country with access to the Black Sea as of 2019. (Map: C. Gonzalez-Esteban)

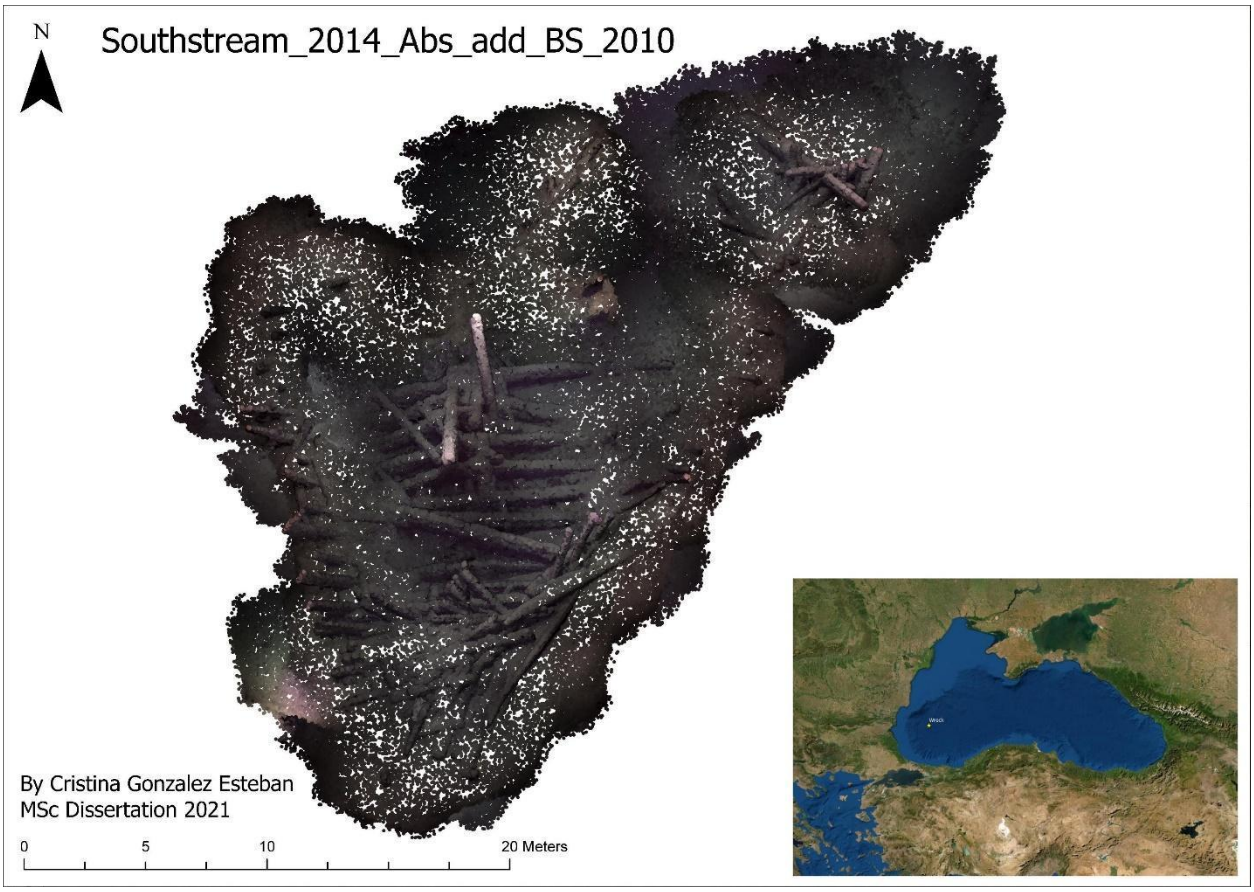

Figure 3: GIS layout created to show the dense point cloud of the Black Sea MAP wreck Southstream_2014_Abs_add_BS_2010, based on the images obtained from the WROV survey and processed through Agisoft Metashape. The small corner image locates the wreck within the Black Sea. (Images: C. Gonzalez-Esteban)

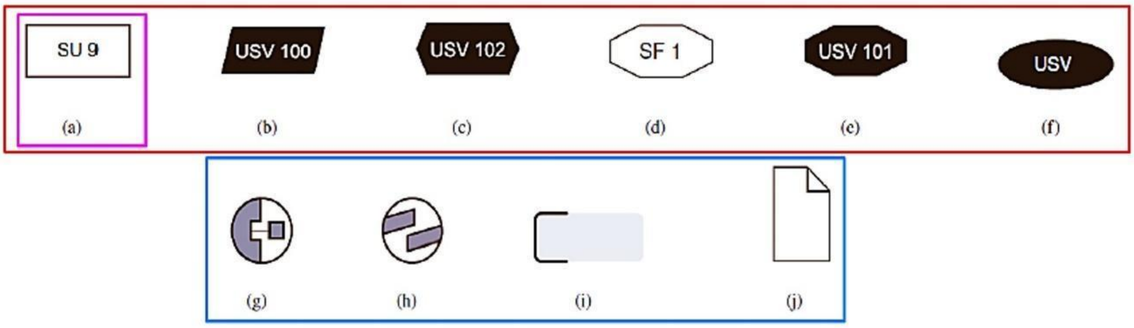

Figure 4: EM nodes published in 2021, representing the metadata nodes (red square), including the Harris Matrix node (pink square), and the paradata nodes (blue square).
(Image: Edited by Cristina Gonzalez-Esteban from Demetrescu, 2015: 48)

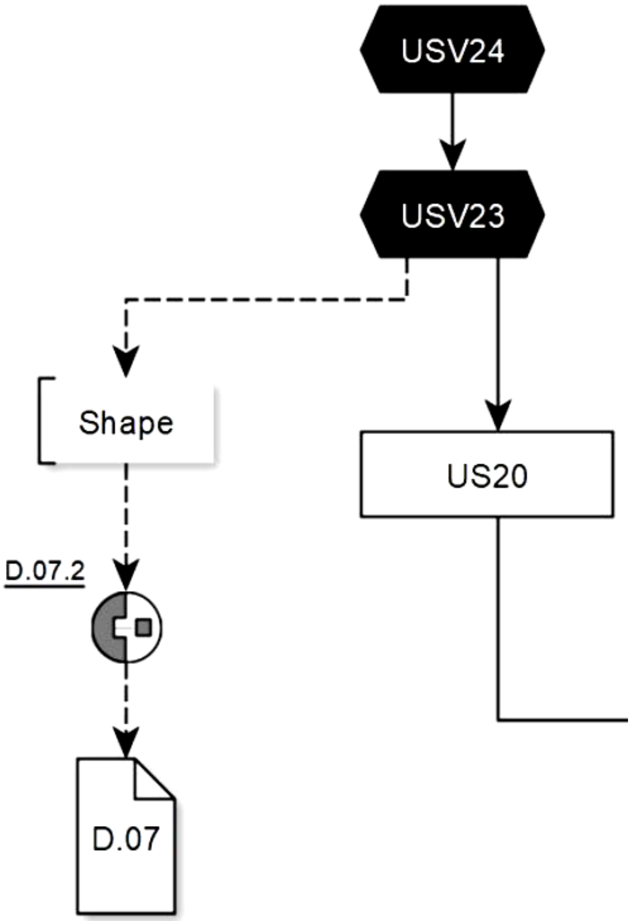

Figure 5: Prototype example of the combination of different nodes to create an EM from an HM stratigraphic unit. The black line represents the link of metadata (direct source) while the dotted line shows the paradata (thought process). (Graph: Cristina Gonzalez-Esteban)

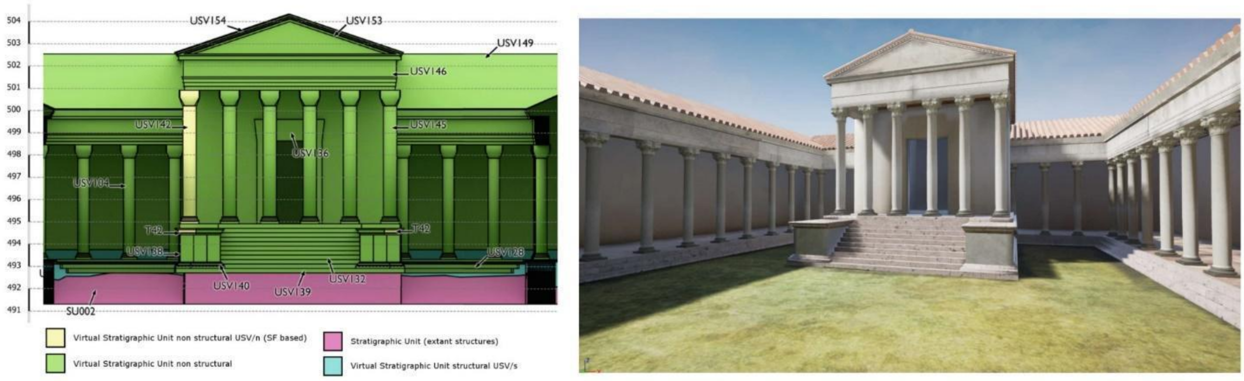

Figure 6: Two ways of visualising the results achieved in the virtual reconstruction of the 2nd century BC Sarmizegetusa Temple, in modern-day Romania. Left: Proxy model with the labels of the USV that links it to the EM and the colour code representing the levels of confidence of the hypothesis. Right: the textured representation model. (Models: Demetrescu, 2018: 109)

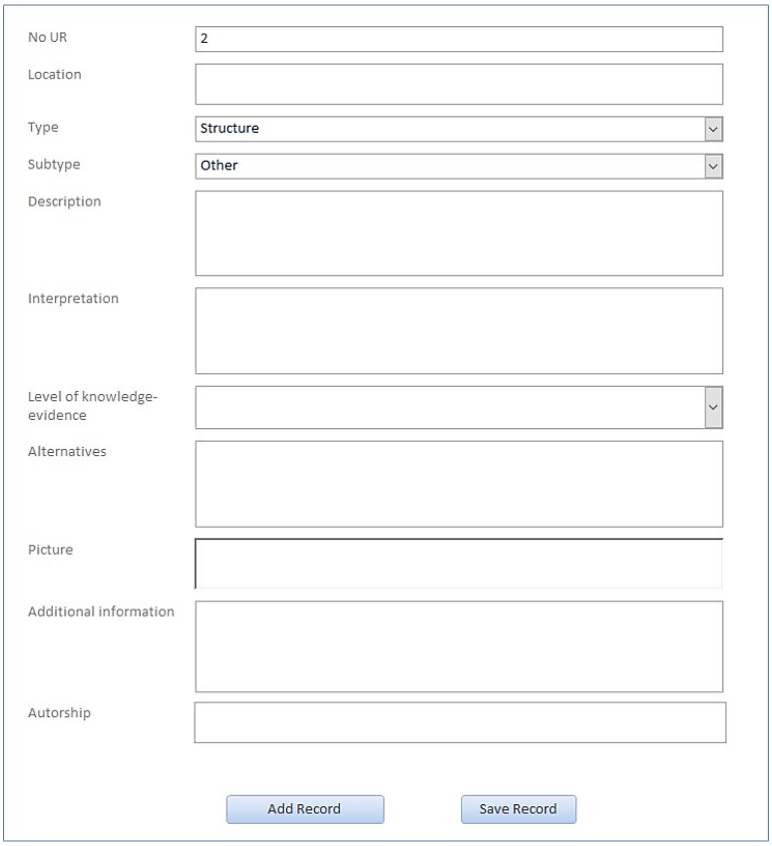

Figure 7: Example of a clean template of the Reconstructive Units in English, made to record the metadata of archaeological virtual reconstructions. (Image: C. Gonzalez-Esteban)

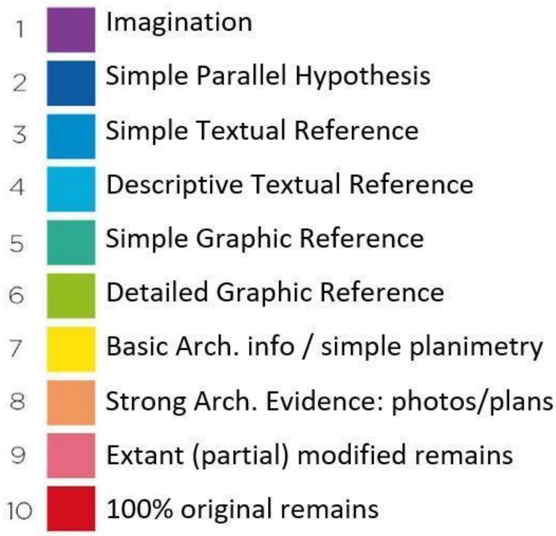

Figure 8: Colour scale proposed for the standardisation of the different levels of reliability of archaeological virtual reconstructions, with their descriptive interpretation as made by Aparicio-Resco and Figueiredo, 2016. (Image: C. Gonzalez-Esteban)

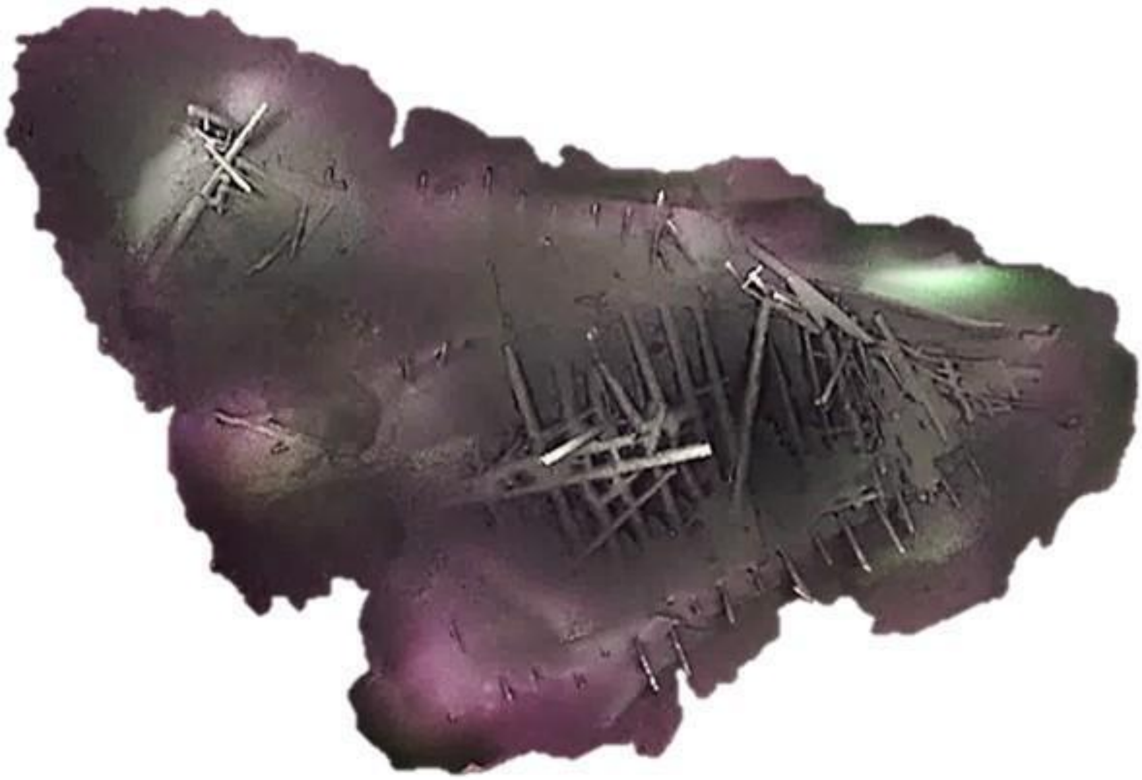

Figure 9: Photogrammetry model of Southstream_2014_Abs_add_BS_2010.
(Images: Black Sea MAP project Team reprocessed by C. Gonzalez Esteban)

D.10	Punta del Francese (Stintino-Sassari) hypothetical reconstruction. 1st century AD (Flavian period) Roman merchant vessel		Articles without details about the wreck just cargo	Beltrame, C., Lazzarini, L., & Antonelli, F. 2020. A Roman shipwreck with a cargo of Apuan marble (marmor lunense) at Punta del Francese (Stintino-Sassari, Sardinia). *Archaeometry,* 62 (6): 1081-1094.	.pdf article
D.11	3D reconstruction proposed for the Roman Ship at Trstenik, gulf of Kaštela, Croatia Late 1st century AD (Imperial Rome) 12-16m long Merchant vessel.		Construction: shell-first mortise and tenons Element: wales + stringers Frames: 15-20cm separation due to intermediate timbers Fastening: treenails Limber holes on the frames as flat bottom vessel	Royal, J. G. 2020. A Roman ship scuttled near Salone in the Gulf of Kaštela, Croatia: Excavation, Reconstruction and Analysis. PhD Thesis: Doctor in Philosophy-Anthropology. Texas A&M University.	.pdf article
D.12	Zwammerdam 4 and Kapel Avezaath 1 1st AD and 2nd AD respectively Roman Cargo vessels		Size: roman cargo vessels of over 30m in length	https://www2.rgzm.de/navis/home/frames.htm#../dbx/Wreck.htm	Online Database entries. NAVIS I
D.13	The Monfalcone wreck 2nd century AD Conserved 10,7m lenght X 3,8 width Roman cargo vessel (found inland)		Construction: shell-first pegged M&T Frames: 16.5 separation Fastening: tree nails and nails	https://www2.rgzm.de/navis/home/frames.htm#../Ships/Ship057/NaveMonfalconeEnglish.htm	Online Database entries. NAVIS I
D.14	Fiumicino 4 2nd-3rd century AD Conserved 7.98m length X 2,79 width Roman coastal trade vessel or fishing boat		Construction: shell-first pegged M&T SMALL: around 8m Frames: 25 separation Fastening: tree nails	https://www2.rgzm.de/navis/home/frames.htm#../Ships/Ship054/Fiumicino4engl.htm	Online Database entries. NAVIS I

Figure 10: Example section of the "Dossier Comparatif" with sources used to develop the reconstruction hypothesis of Southstream_2014_Abs_add_BS_2010. (Table: C. Gonzalez-Esteban)

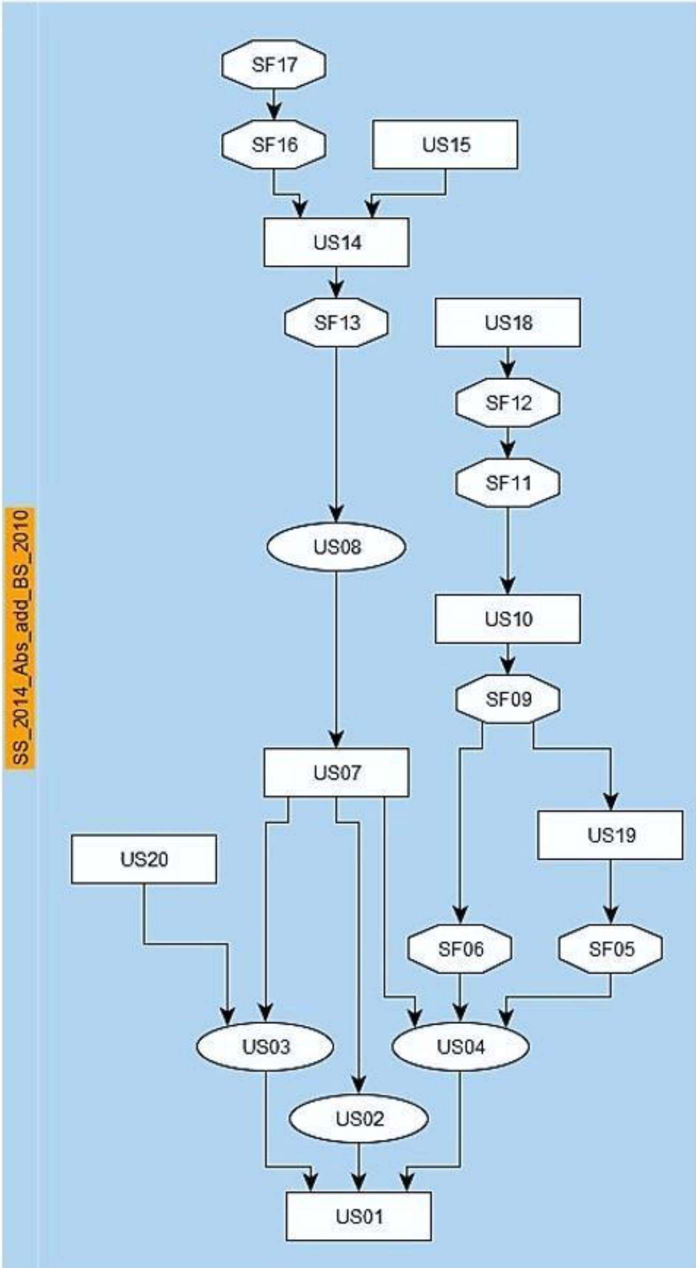

Figure 11: Harris Matrix of the construction sequence of Southstream_2014_Abs_add_BS_2010 done using yEd software. This is the base to keep building up the reconstruction (Extended Matrix). (Diagram: C. Gonzalez-Esteban)

No UR	5020
Location	Rec. SS_2014_Abs_add_BS_2010 Black Sea MAP wreck
Type	Accessories
Subtype	Wooden object
Description	Bowsprit Mast + Boom
Interpretation	Bowsprit Mast + Boom
Level of knowledge-evidence	05-Basic graphic evidence
Alternatives	
Picture	
Additional information	To know the sources that support this hypothesis, please see the Extended Matrix of the reconstruction
Autorship	Author of the Dissertation: Cristina Gonzalez Esteban

Figure 12: Example of an RU created for one of the elements found among the remains of Southstream_2014_Abs_add_BS_2010: namely, the broken frames on the port side. (Sheet: C. Gonzalez-Esteban)

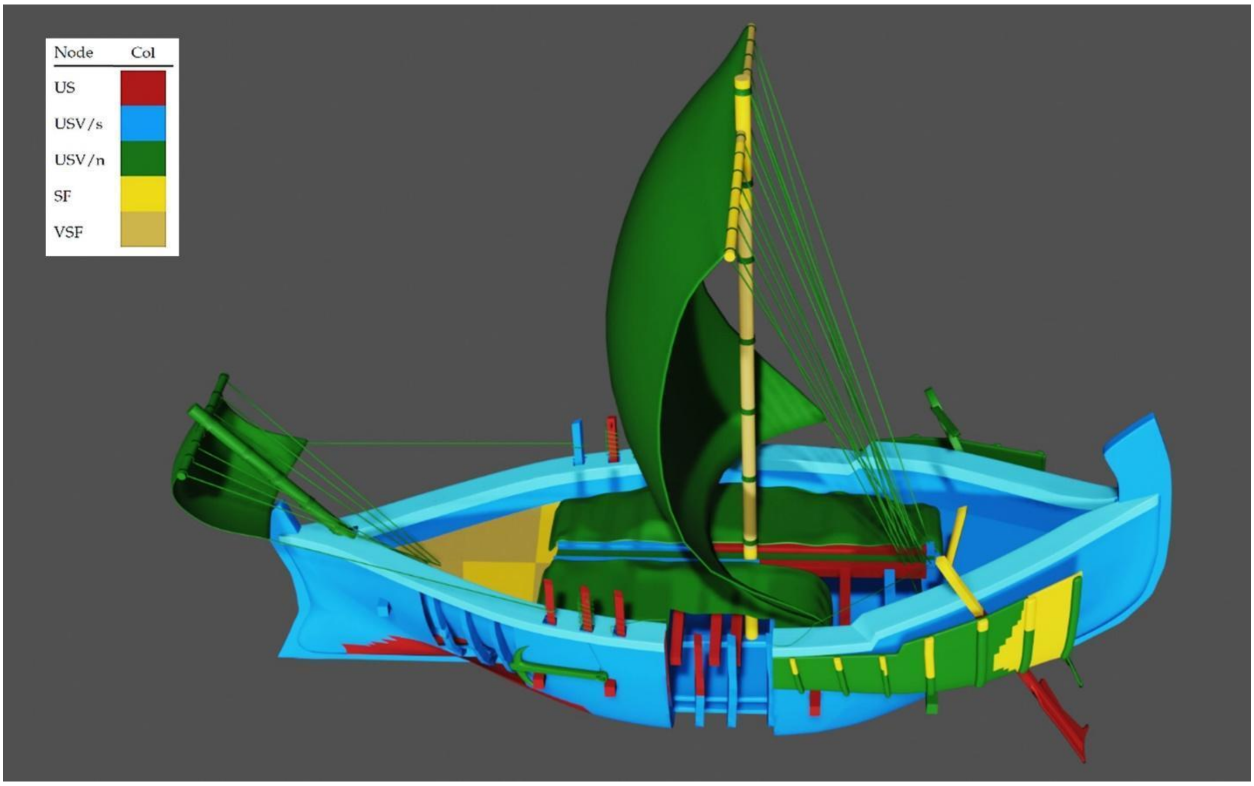

Figure 13: 3D model of the reconstruction of Southstream_2014_Abs_add_BS_2010, textured using the automatic colour scheme of the nodes from the EM: US is red, USV/s is blue, USV/n is green, SF is yellow and VSF is golden. (Model: C. Gonzalez-Esteban)

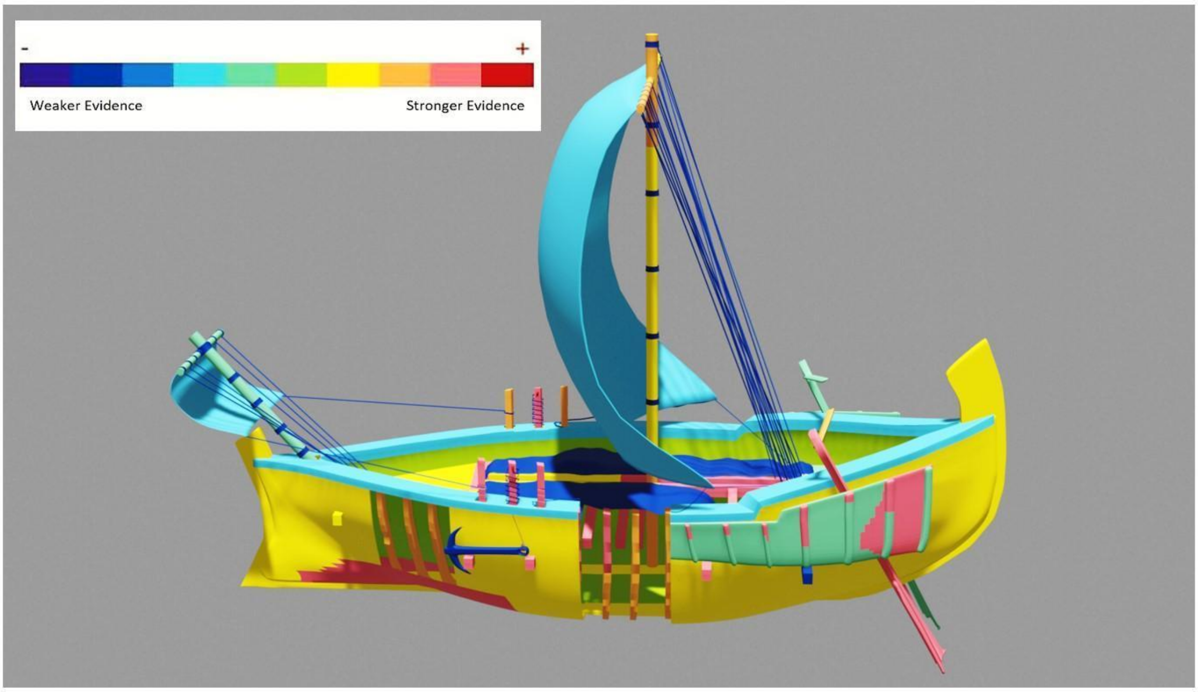

Figure 14: 3D model of the reconstruction of Southstream_2014_Abs_add_BS_2010, textured using the colour ramp of the Graphic Scale of Evidence (GS): warmer colours represent higher degree of reliability of the source, while cooler colours show less reliability. (Model: C. Gonzalez-Esteban)

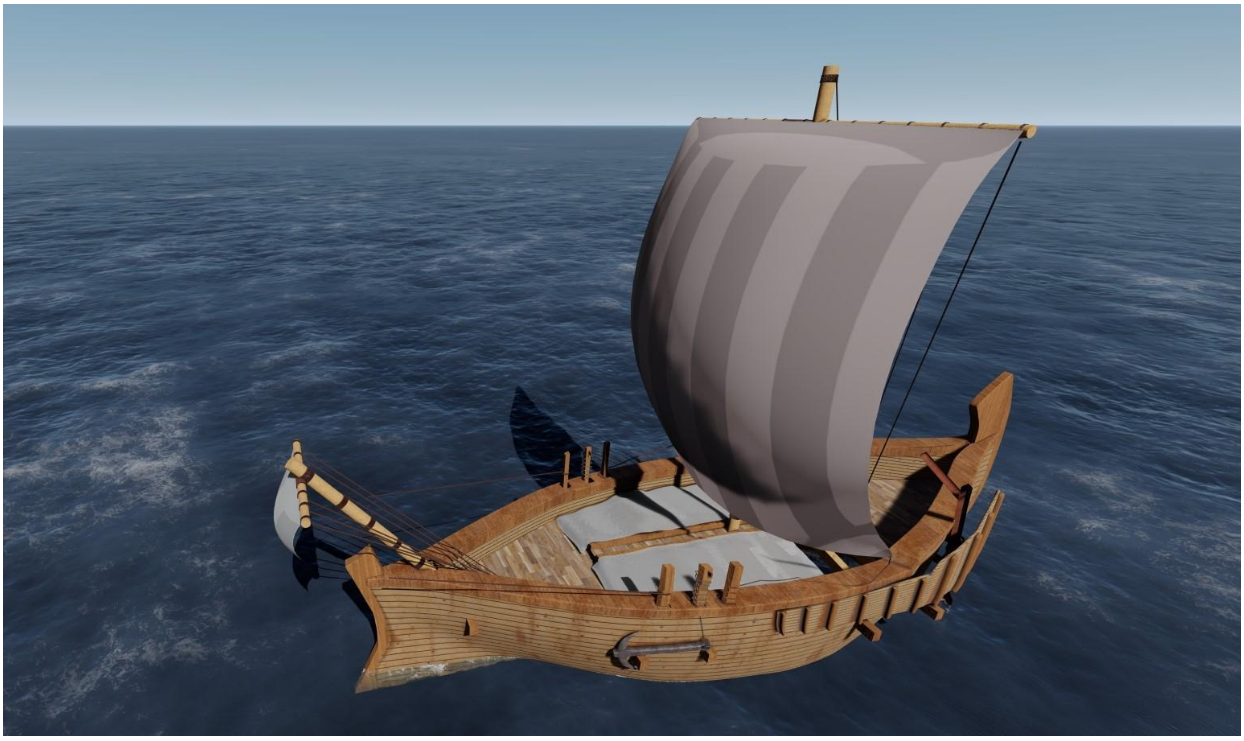

Figure 15: Render of the final textured reconstruction proposed for the Southstream_2014_Abs_add_BS_2010 wreck from the Black Sea MAP project. (Render: C. Gonzalez-Esteban)

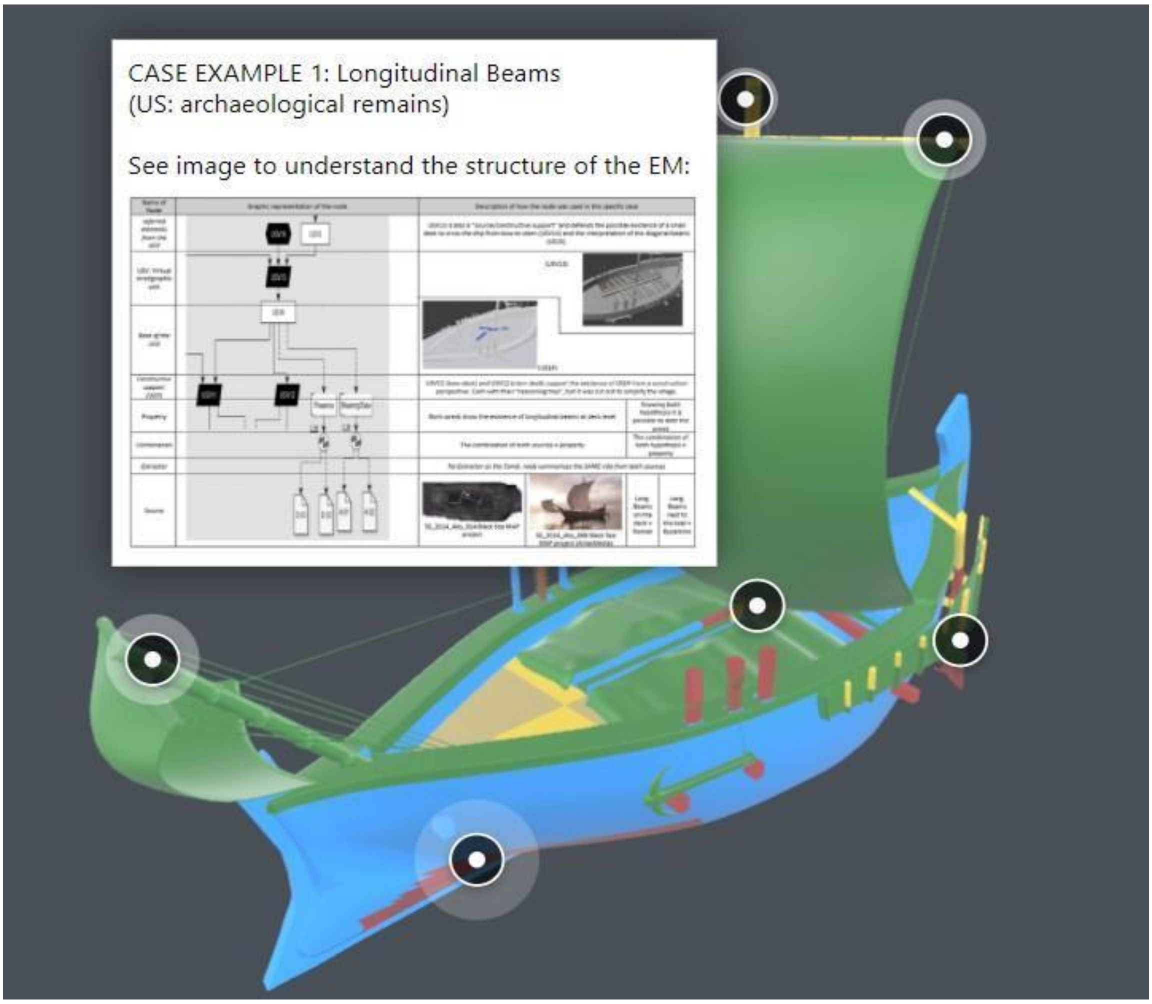

Figure 16: Screenshot of the EM mode, as part of the research "Virtual Tour" created using ThingLink of Southstream_2014_Abs_add_BS_2010, together with its QR code for easy access. (Model: C. Gonzalez-Esteban)

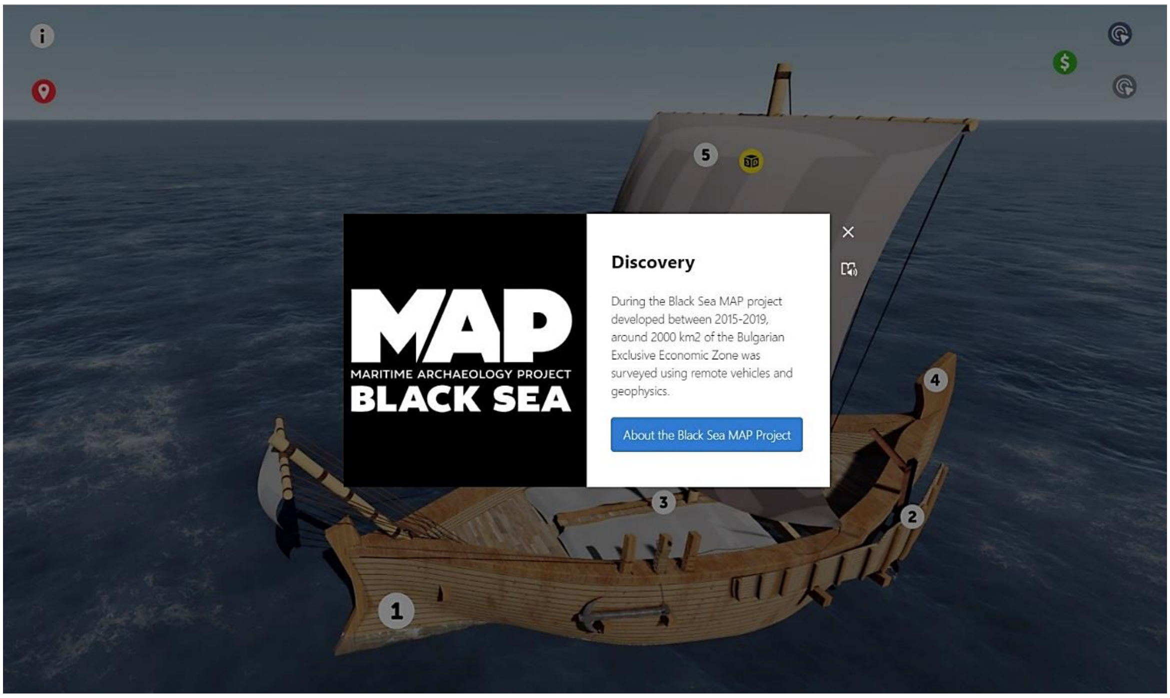

Figure 17: Screenshot of the public engagement virtual tour created using ThingLink of Southstream_2014_Abs_add_BS_2010. It is interactive, straightforward, and contains short descriptions of the wreck and the MAP Black Sea project. (Model: C. Gonzalez-Esteban)

Figure 18: Photograph of the set built with the 3D printed models of Southstream_2014_Abs_add_BS_2010. The two small boats measure 12 cm in length, while the central model of the wreck's remains is 24 cm. (Photo: C. Gonzalez-Esteban)

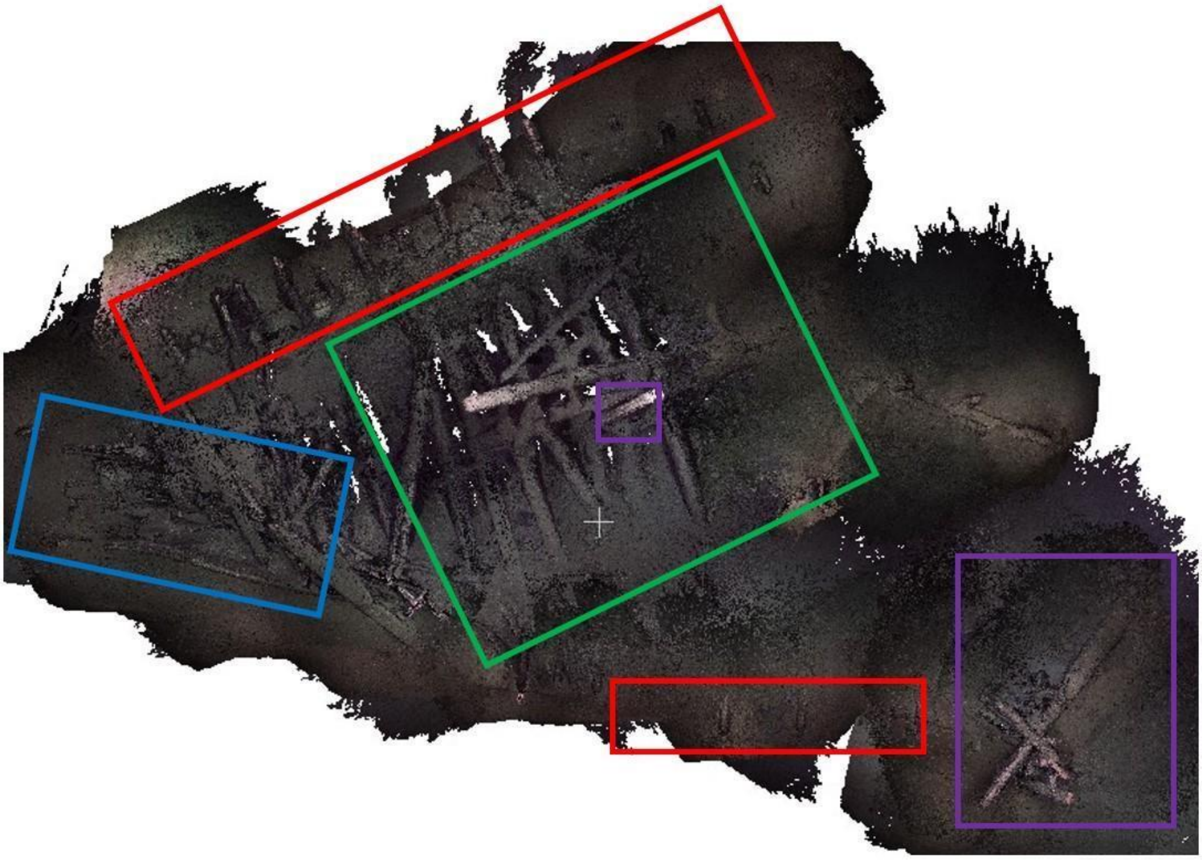

Figure 19: Image of the photogrammetry model of Southstream_2014_Abs_add_BS_2010, marking the four main areas of research: blue: planking and construction sequence; red: frame shape and placement; green: internal structure; purple: propulsion and steering. (Image: C. Gonzalez-Esteban)

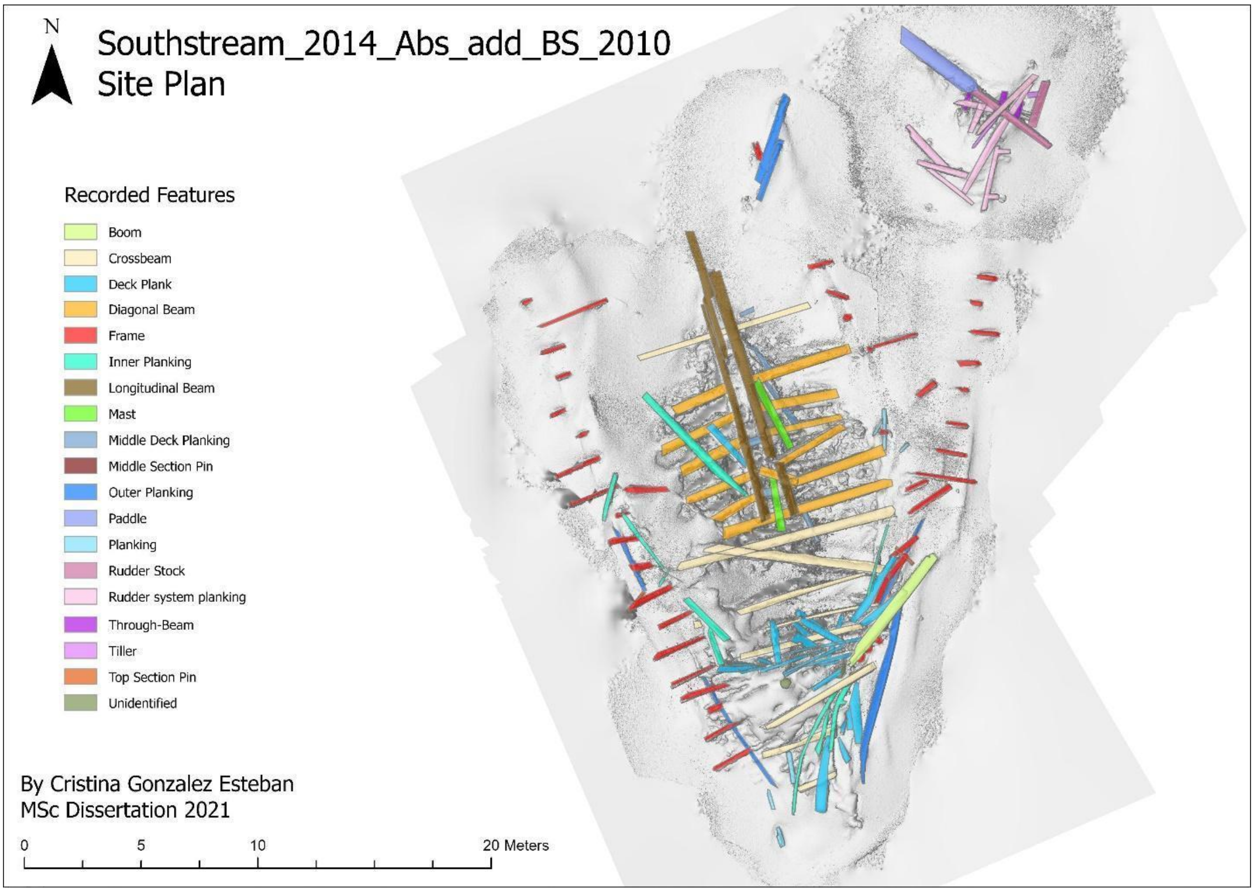

Figure 20: GIS site plan drawing of the interpreted remains from Southstream_2014_Abs_add_BS_2010, displayed over the hillshade map created from the DEM of the photogrammetry model. This was done based on the data provided by the University of Southampton. No images of the finds have been added to this article to avoid issues with copyrights. (Drawing: C. Gonzalez-Esteban)

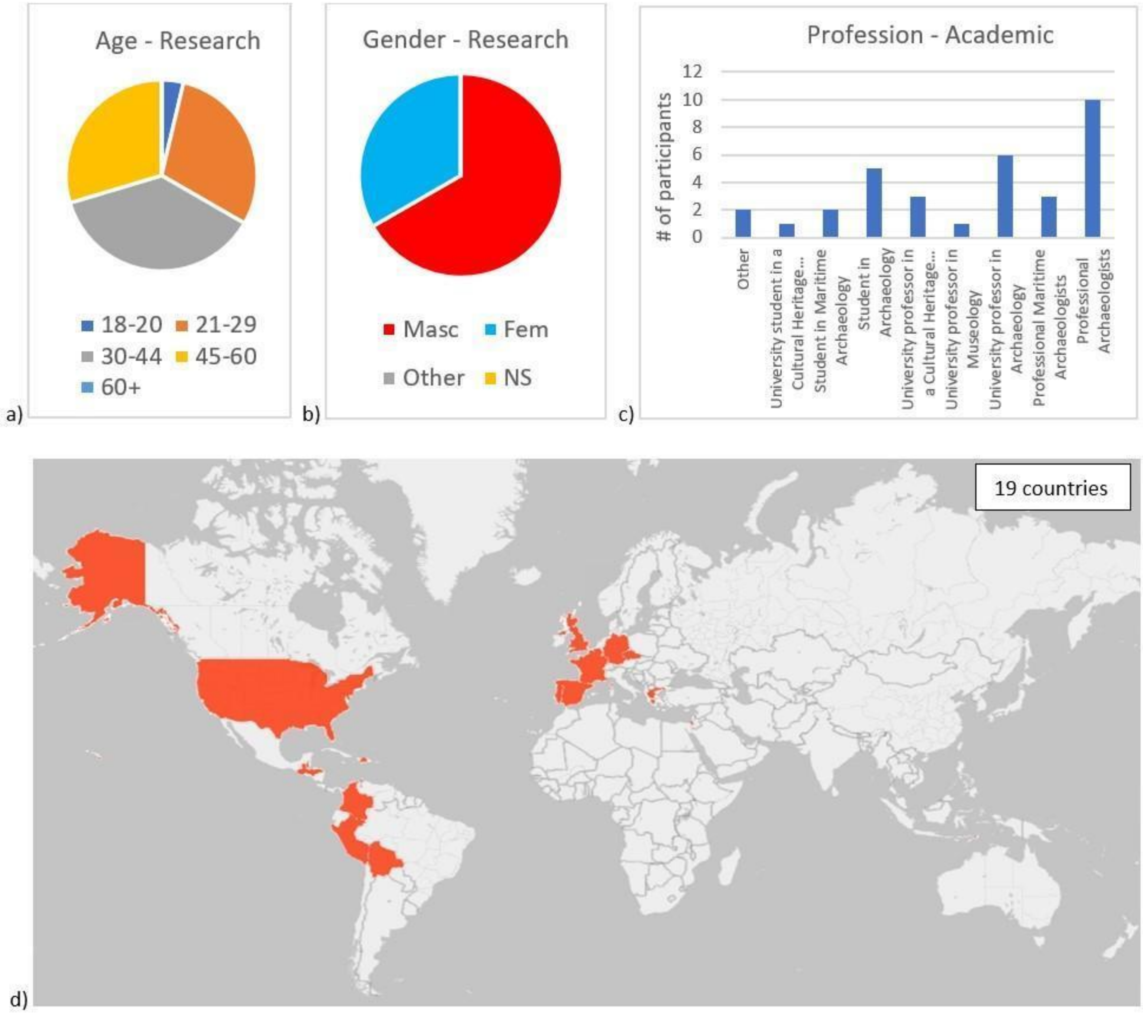

Figure 21: Graphs showing the basic information of the participants of the research questionnaire: a) age; b) gender; c) country of work; d) profession.
(Charts: C. Gonzalez-Esteban)

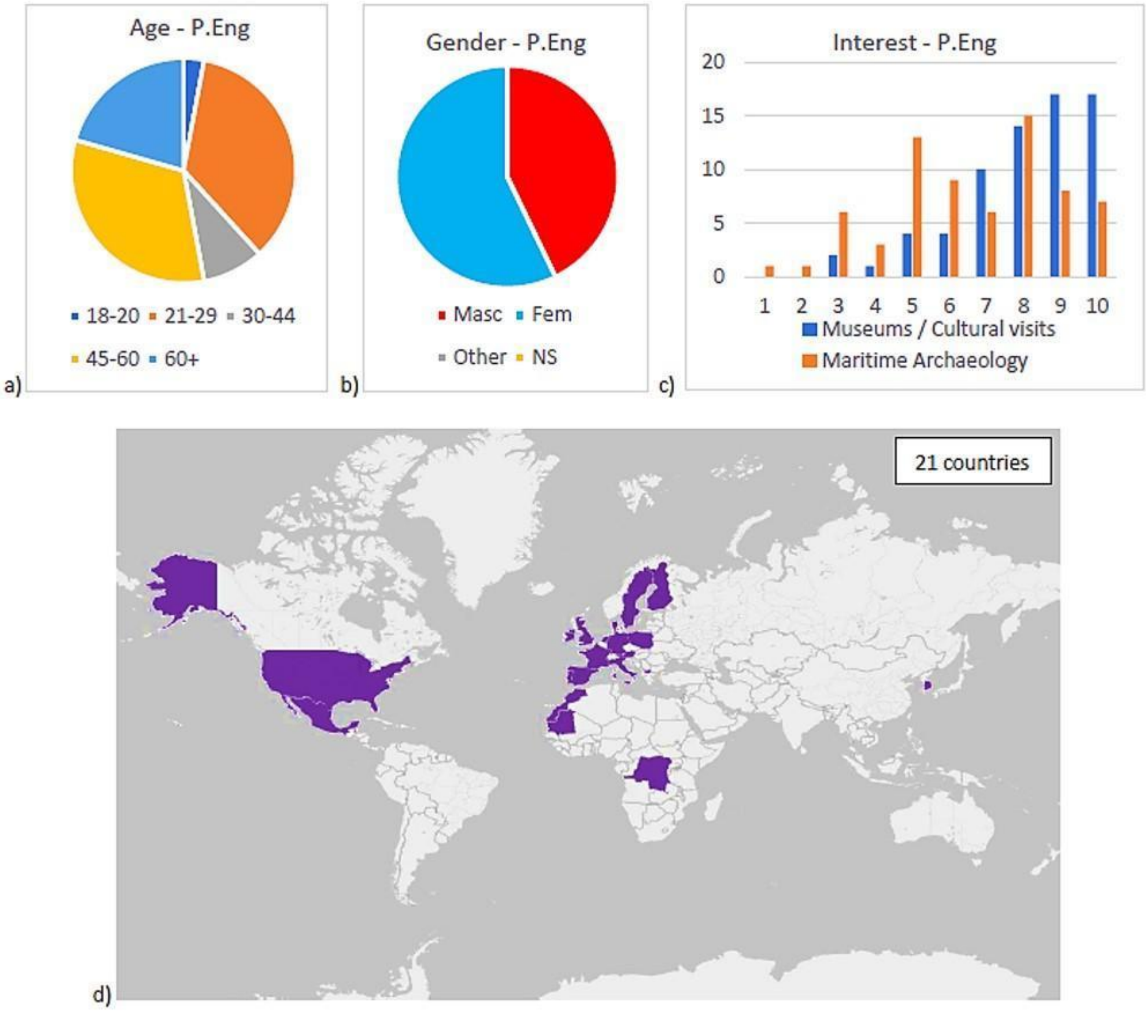

Figure 22: Statistics showing the basic information of the participants of the public engagement questionnaire: a) age; b) gender; c) country (growing up or 3+ months); d) interest in museums and maritime archaeology. (Charts: C. Gonzalez-Esteban)

Tables

Table 1: Table showing the differences between reality-based models and source-based models. (Table: Cristina Gonzalez-Esteban)

	Reality-based models	Source-based models
Also known as (in other disciplines)	Digital twins	Research-led
To develop	Surveys and recordings	Virtual Reconstructions
Equipment	Digital acquisition equipment: laser scanners, photographs	Computer graphics
Target: document, visualise and interpret…	Existent archaeological contexts	"Lost" archaeological contexts
Represents	The real world	Hypothesis
Accuracy	Expressed in measuring units (*e.g.* 1.5mm)	NOT expressed in real units. Depends on the reliability of the sources used

Table 2: Examples of projects that have reported the usage of some kind of metadata recording methodology for their reconstructions. (Table: Cristina Gonzalez-Esteban)

Project	Reconstructive Units (Molina-Vidal and Muñoz-Ojeda 2015)	Graphic Scale (Aparicio-Resco and Figueiredo 2016)	Extended Matrix (Demetrescu and Ferdani 2021)	References
Tepidarium of the Eastern Thermae of L'Alcudia de Elche	YES	YES	YES	Gonzalez-Esteban, 2019
Roman Villa of Aiano (San Gimignano, Italy)			YES	Demetrescu and Ferdani, 2021

Project	Reconstructive Units (Molina-Vidal and Muñoz-Ojeda 2015)	Graphic Scale (Aparicio-Resco and Figueiredo 2016)	Extended Matrix (Demetrescu and Ferdani 2021)	References
Roman Villa at L'Albir (Alicante, Spain)			YES	*In prep*
Roman Villa out of Porta Marina (Ostia, Italy)			YES	Demetrescu and Ferdani, 2021
Temple A of Illeta dels Banyets (El Campello, Alicante, Spain)		YES		Aparicio-Resco and Figueiredo, 2016
Imperial Forum of Augustus (Rome, Italy)			YES	Demetrescu and Ferdani, 2021
German WW2 bunker H669 (*no location*)	YES	YES		Aparicio-Resco and Figueiredo, 2016
Onde Marine, Necropolis of Banditaccia (Cerveteri, Italy)			YES	Demetrescu and Ferdani, 2021
1st Phase of the Santiago Domus (Bracara Augusta, Braga, Portugal)		YES		Aparicio-Resco and Figueiredo, 2016
Amba Aradam (Rome, Italy)			YES	Demetrescu *et al.*, 2021
Door-Tower of Bejanque (Guadalajara, Spain)	YES	YES		Aparicio-Resco and

Project	Reconstructive Units (Molina-Vidal and Muñoz-Ojeda 2015)	Graphic Scale (Aparicio-Resco and Figueiredo 2016)	Extended Matrix (Demetrescu and Ferdani 2021)	References
				Figueiredo, 2016
Great Temple (Sarmizegetusa, Romania)			YES	Demetrescu and Ferdani, 2021
Craft Building (Montebelluna, Italy)			YES	Demetrescu and Ferdani, 2021
Porticus Post Scaenam. Roman Theatre of Merida (Spain)				Gaspar-Rodriguez, 2020
Amphitheatre of Cartagena (Murcia, Spain)				Simon-Garcia, 2021