Agent-based modelling for the study of shipwreck site formation processes: A theoretical framework and conceptual model. [version 1; peer review: 2 approved with reservations]

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Abstract

Background
Shipwreck site formation processes (SFP), their dynamics and transformation have long interested maritime archaeology from both a historical perspective and heritage management since shipwrecks constitute endangered cultural sites. Major contributions to shipwreck SFP have been made since the 1970s which conceive SFP from a systemic theoretical perspective, notably those of Keith Muckelroy and Martin Gibbs. However, to our view, such a perspective falls short in its capacity to explain and predict the distribution of elements in a shipwreck. In this article, we propose that shipwreck SFP can be understood from the theoretical framework of complex adaptive systems (CAS), where a SFP constitutes a CAS in which nonlinear interactions of natural and cultural factors give rise to the observed seabed distribution of a shipwreck as an emergent phenomenon.

Methods
From this theoretical framework, we propose agent-based modelling (ABM) as a suitable methodological approach for studying SFP. We show its implementation using the USS Somers, a 19th-century brig of war that sank in 1846 off the port of Veracruz, Mexico, during the Mexican-American War as a case study. The conceptual model was developed from the integration of historical data about the ship's nautical characteristics and operation, information on the wrecking event from eyewitnesses, as well as modern environmental data.

Results
We present a conceptual model defining various elements that would constitute the Somers' ABM. It gives specifics about the characteristics and variables regarding agents, global variables, processes, indicators, degradation and deposition sequences, and user interface.

Conclusion
The conceptual model served to develop ABM in a simulation platform where historical hypotheses can be tested and various possible
scenarios of the SFP can be explored. By contrasting the simulation results with the archaeological record of the shipwreck, ABM would allow maritime archaeologists to postulate more supported and refined interpretations of a shipwreck's SFP.

**Keywords**
Shipwreck, site formation processes, agent-based modelling, simulation, complex adaptive systems, maritime archaeology, cultural heritage, Mexican-American War

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1. Introduction

In maritime archaeology, the study of shipwreck site formation processes (SFP) has been a central topic of interest since the beginning of the discipline and has been undertaken by different scholars, and under different theoretical influences. Many authors have made key contributions to the subject, notably Keith Muckelroy in the 1970s and Martin Gibbs in the first decade of the 21st century. These authors’ SFP models were conceived from a classical systemic theoretical perspective. A system is considered an “intercommunicating network of attributes or entities forming a complex whole. [Entities] states or values change sequentially with space, time, or both and consequently the overall system state changes”. While this perspective revolutionised maritime archaeological thinking during the last quarter of the 20th century, to our view falls short in its capacity to explain and predict the distribution of elements in a shipwreck.

In this article, we propose that a step forward can be taken beyond the classical standpoint of systems theory to conceive shipwreck SFP as complex adaptive systems (CAS). In the next section, we argue that SFP indeed show features of CAS, where the interaction of large networks of components, without central control and simple operating rules, gives rise to complex collective behaviour, information processing, and adaptation. When conceiving SFP as CAS, using methodological tools that allow simulating their non-linear interactions and emerging properties becomes necessary. One such tool is agent-based modelling (ABM), which is particularly useful when the system is made up of a medium and heterogeneous number of individuals, with complex but local interactions that occur in an environment with many interaction possibilities, such as natural environments.

We then present a conceptual model for developing an ABM for studying shipwreck SFP, taking the 19th-century brig-of-war USS Somers (1846) as a case study. This research is part of the Proyecto Arqueología Marítima de la Guerra de Intervención (1846-1848) (PAMGI), a maritime archaeology project developed by the Institute of Anthropological Research within the National Autonomous University of Mexico (IIA-UNAM), and with support from UNAM, the British Academy, the Mexican Science Council (Conacyt) and in collaboration with the Centre for Maritime Archaeology, University of Southampton. The project studies the nineteenth-century Mexican-American war not only from a maritime archaeology perspective but also from conflict, historical, and maritime landscape archaeology viewpoints. Although the project works with sites on land, rivers, and seas, a particular emphasis has been devoted to the Somers, from an array of different archaeological and historical perspectives, including SFP. By analysing the Somers’ shipwreck SFP through ABM, it is possible to better understand the interactions between various social and natural elements in its formation as an archaeological site.

Finally, we discuss some of the conceptual model’s limitations and potential extensions; and conclude by highlighting our proposal’s theoretical and methodological contribution to archaeology in general, and maritime archaeology in particular.

1.1 Theoretical framework

1.1.1 Shipwreck site formation processes

SFP have been a topic of study in archaeology since the 1970s for understanding “what kinds of intercultural and intracultural variables determine the structure (as distinct from the form and content) of the archaeological record”. In maritime archaeology, the early study of shipwreck SFP focused on natural processes to understand the relationship between element disposition and preservation in a shipwreck and its surrounding environment. A three-stage scheme was proposed by Frédéric Dumas for understanding SFP of Mediterranean shipwreck sites, covering from the ship’s sinking to its eventual disintegration and collapse on the seabed.

Dumas’ scheme provided the basis for later models of shipwreck SFP. At the end of the decade, British maritime archaeologist Keith Muckelroy published a seminal model for understanding how it is that “a highly organised and dynamic assemblage of artefacts [the sailing ship] is transformed into a static and disorganised state with long-term stability [the shipwreck site]”. Based on the theoretical postulates of David L. Clarke, Muckelroy’s model sought:

“ [...] to identify the several features common to any shipwreck [...]. Just as the nature of a ship involves certain basic concepts which are common to all periods and places, so the phenomenon of the shipwreck must involve certain regular features common to all instances. [...] The validity of any conclusions reached in maritime archaeology depends fundamentally on the understanding of these processes, so that their study must occupy a central place in the sub-discipline.”

In Muckelroy’s model (Figure 1), shipwreck SFP was conceived as a system in which the ship (input) transforms throughout time by the action of environmental factors (the medium where the wreck took place), extracting filters (those that remove material from the site) and scrambling devices (that rearrange or modify artefacts’ spatial disposition).
Thus, the process generates the assembly of artefacts observed on the seabed as output (i.e., the site itself). Similar to Dumas’ proposal, a central element in Muckelroy’s model of shipwreck SFP is the surrounding environment, demonstrating the importance of considering the characteristics and dynamics of the maritime environment when studying shipwreck SFP. However, to our view, this is a limited conception of the process since the overall element distribution is not predictable from the individual elements and the sub-processes alone. We will delve into this in the next section when discussing complex adaptive systems and emergent phenomena.

Despite its limitations, Muckelroy’s model represented a milestone in the study of shipwreck SFP. In the following decades, various authors developed and expanded certain aspects of Muckelroy’s model. Keith and Simmons extended the concept of “extractor filters” when distinguishing between object removal operations that occurred in antiquity and those of modern times. Later, Souza analysed the cultural factors that affect shipwreck distribution, considering pre-depositional processes such as risk minimisation strategies, depositional and post-depositional processes including the intentional abandonment of objects and their subsequent recovery, and priorities in both ancient and modern salvage operations. In the early 2000s, O’Shea explored various alternative scenarios based on different types of human intervention, including salvage and search for objects by the original crew in contrast to those carried out by others, and considered the temporal sequence of said activities.

For Australian maritime archaeologist Martin Gibbs, Souza and O’Shea’s analyses based on the three sub-processes proposed by Muckelroy were still oriented towards explaining the deposition and distribution of the wreck rather than towards the cultural processes involved in the changes suffered by the site through time. Hence, in 2006 he proposed an alternative model for understanding shipwrecks as the result of a cultural process, based on both the nature of the shipwreck event and the sequence and scope of potential responses at each stage.

Gibbs based his model on anthropological studies of human responses to disasters to incorporate the attitudes and responses that people would have before, during, and after the shipwreck into Muckelroy’s general scheme (Figure 2). Thus, before the event of the shipwreck itself, not only is the ship considered, but also the actions and decisions that are taken to prevent and avoid the disaster. Immediately before and during the shipwreck, he considers the abandonment and salvage of objects in light of the diverse reactions and interests of the various crew members and passengers. After the disaster, the regrouping and reorganisation of the survivors begins, giving rise to formal rescue actions that can generate

independent but associated sites, such as camps and temporary warehouses. Only after all of these social processes have ended that naturally occurring processes, on which traditional research on shipwreck SFP has focused, begin to act on the ship's remains, including sediment deposition or biological colonisation.13

A decade later, Gibbs himself, along with fellow Australian maritime archaeologist Brad Duncan, supplemented the original model by adding other processes in addition to salvage, that can account for the fate of a ship. These include hulk abandonment and intentional stranding or break-up.2 They also delved into the different motivations that people who carry out different types of rescue may have, which adds to the understanding of the cultural elements involved in SFP.2

1.1.2 Complex adaptive systems

In the last quarter of the 20th century, the field of research that we now call complex systems arose to address the need for studying a wide variety of natural and social phenomena that cannot be understood or explained from the mechanistic and reductionist worldview that has dominated science since the seventeenth century. This field seeks to “[...] explain how large numbers of relatively simple entities organise themselves, without the benefit of any central controller, into a collective whole that creates patterns, uses information, and, in some cases, evolves and learns”.4

Figure 2. “Cultural factors in shipwreck site formation.” From Ref. 13 reproduced with permission from the author.
Although CAS can be very different from each other in their particular details, at an abstract level it is possible to identify certain common properties and thus define them as systems “[…] in which large networks of components with no central control and simple rules of operation give rise to complex collective behaviour, sophisticated information processing, and adaptation via learning or evolution”.  Furthermore, such collective behaviour “is not predictable from the elements themselves” but arises “through the interaction of the multiple distributed elements”. Hence, this type of behaviour is called an emergent phenomenon, which is a characteristic of CAS.

In both Muckelroy and Gibbs’ models, shipwreck SFP show many of the characteristics of CAS. They involve a series of elements (ship, contemporary actors, environment, future actors), which are subsystems in themselves, whose interactions within the process change over time, generating phenomena that are not predictable from the mere presence of said elements, one of these phenomena being the observable spatial distribution in the wreck. Therefore, in this work we take the theoretical perspective of CAS, particularly on the notion of emergent phenomena, to address shipwreck SFP.

In maritime archaeology, very few researchers have explicitly adopted the theoretical perspective of CAS. In the late 1990s, Jorge M. Herrera used this perspective to analyse the regional-scale spatial distribution of submerged cultural remains in the keys of Campeche, Mexico. Later, together with archaeologists Valerio Buffa and Alejo Cordero (Uruguay) and Jonathan Adams (UK), the first maritime archaeology research program in Uruguay carried out by fully trained maritime archaeologists was designed and implemented from the perspective of CAS, with fieldwork being carried out at both regional and site scales. Currently, the theoretical perspective of CAS is a central part of PAMGI.

In Germany, Johannes Preiser-Kapeller and colleagues have used the CAS perspective as a theoretical platform to study ancient Mediterranean ports. Preiser developed non-linear models to study the internal dynamics of ports (their establishment, maintenance, and use) and navigation and exchange routes through network models. Recently, Rodrigo Ortiz-Vázquez in the UK developed a methodology for the study of wreck site formation processes based on CAS. We will give more details about this work in the next section.

1.1.3 Site formation processes as CAS

In our view, all SFP can be considered as CAS, the interacting elements within the system being both natural and social, and the observable characteristics of all archaeological contexts as emergent phenomena. In the case of shipwrecks, elements include: the ship, with its specific configuration and a myriad of individual components; the people of the past, those directly or indirectly involved in the design, construction, and operation of the ship with their motivations, beliefs, and decisions; the environment, with its bathymetry, edaphology, currents, storms, temperatures, flora, and fauna (benthic and pelagic); and the people of the future, those who visit the wreck, be it to loot, dive, or study it.

All these elements make up the CAS constituting agents that interact at one time or another in the SFP. Furthermore, each of them may be a CAS in itself, although on a different scale, thus showing the self-similarity of the process, which is also characteristic of CAS. The result of these interactions, changing in magnitude and frequency over time, is an emerging phenomenon: the distribution of elements observable by the archaeologist at the site. But this also changes over time and, in turn, its configuration affects agents and their interactions. For this reason, the configuration of an archaeological site is not a static time capsule or fossil record as Lewis Binford would have suggested, but a dynamic one, and it is not predictable from the individual or aggregate characteristics of its composing elements. The shipwreck is more than the sum of its parts; it is a CAS.

One of the challenges when approaching the study of the emerging phenomena of a CAS is the so-called differential or compositional understanding of the phenomenon. This refers to trying to determine the behaviour of the elements (agents) that gives rise to the pattern that is observed (emergent phenomenon). In the case of shipwreck SFP, we try to understand what the characteristics of the elements and the interactions that occurred over time were, which gave rise to the wreck that archaeologists now observe. Shipwreck SFP have relied heavily on the archaeological record derived from survey, excavation, and/or artefact analysis. Different record types generate data of a different nature, amount, and level of detail, and one of the challenges in studying SFP has been integrating such a variety of data to achieve a consistent interpretation of the process.

In this sense, Rodrigo Ortiz-Vázquez recently developed a methodology for the integration and analysis of information for the study of shipwreck SFP, which explicitly starts from conceptualising them as CAS. Ortiz-Vazquez’s proposal integrates larger-scale information about the site, from historical documents (maps, charts, descriptions), with medium-scale data provided by marine geophysical techniques (multibeam echosounder) and smaller-scale, intra-site data from the photogrammetric record, laser scanning, or excavation. By successfully applying his methodology to three case studies, the 18th-century shipwrecks of the Hazardous Prize (1706), the Rooswijk (1740), and the HMS Invincible
Ortiz-Vazquez’s methodology allows analysing a shipwreck’s SFP at different scales, at a three-dimensional level, and over time. This provides much greater detail both to propose solid interpretations of the natural and cultural dynamics that have given rise to wrecks as emerging phenomena, and to their management as cultural resources.

But what happens when the historical information and/or the archaeological record of a shipwreck is limited? How can we have such differential understanding and venture interpretations about its SFP when the scarcity of data makes diachronic analyses difficult? How to approach the study of SFP when we only know, for example, some components of the CAS present at the beginning (the ship, the environment) and the emerging phenomenon at the end (the archaeological record of the wreck)?

To tackle these questions, together with the theoretical framework of CAS, we propose using a methodological approach of computational modelling and simulation as a means of studying shipwreck SFP. We have implemented such an approach to analysing the shipwreck of the 19th-century brig-of-war USS Somers (1846), which we describe further ahead.

1.1.4 Agent-based modelling as a tool for studying CAS

Various types of modelling tools are often used to study CAS and its emerging phenomena, which tend to start from similar principles, but differ in their assumptions and solutions. For example, both equation-based models (EBM) and statistical models assume that the elements of the system are relatively homogeneous with little variability between cases, so they use measures of central tendency to characterise each element. However, there are many cases where the system is highly influenced by the heterogeneity of the elements, particularly in social systems. EBM are also usually continuous, not discrete, so they often require relatively large numbers of individuals to function without reaching logically impossible limits, such as having fractions of individuals. Due to these and other limitations, when the system under study is comprised of a relatively medium number of heterogeneous elements, it is better to use discrete models that are closer to natural conditions, such as agent-based models.

Agent-based modelling (ABM) is a computational tool that allows modelling CAS in order to understand both the rules that configure them and the emerging phenomena that arise from them.

“...The core idea of Agent-Based Modeling is that many (if not most) phenomena in the world can be effectively modeled with agents, an environment, and a description of agent-agent and agent-environment interactions. An agent is an autonomous individual or object with particular properties, actions, and possibly goals. The environment is the landscape on which agents interact and can be geometric, network-based, or drawn from real data. The interactions that occur between these agents or with the environment can be quite complex. Agents can interact with other agents or with the environment, and not only can the agent’s interaction behaviors change in time, but so can the strategies used to decide which action to employ at a particular time. These interactions are constituted by the exchange of information. As a result of these interactions, agents can update their internal state or take additional actions.”

ABM is particularly useful when the system under study is composed of a medium and heterogeneous number of individuals, whose interactions are complex but local (depending on the history of the individuals or their individual properties) and occur in a rich environment, i.e., an environment that has many properties or that provides various possibilities for interaction, as in natural geographic environments.

Interestingly, archaeology was one of the first disciplines in which ABM was applied when this tool was developed at the Santa Fe Institute in the 1990s. It was employed to study the population dynamics of the Anasazi culture that occupied the Long House Valley in Arizona, by comparing the settlement distribution from the simulations with that from the archaeological record. Since then, ABM has continued to be used as a tool to understand various social processes from the archaeological record, particularly in the areas of prehistoric and hunter-gatherer populations.

However, to date, ABM has not been applied to the study of shipwreck SFP despite the fact that, as aforementioned, it is possible to observe all the features that characterise a CAS in them. To our knowledge, computer simulations have only been used in shipwreck SFP to understand its fluid dynamics aspect. Using a computational fluid dynamics model based on the topography of a shipwreck, sediment, and stream flow data, Quinn and colleagues have shown how the interaction of a wreck with ocean currents and the seabed where it was deposited results in the formation of different types of scouring signatures. However, their studies use only fluid dynamics models, not ABM, as a simulation tool.
1.2 The USS Somers case study

The Mexican-American War took place between 1846 and 1848, defining the territory, politics, and economic powers of Mexico and the United States (not to say the entire American continent) for the remainder of the 19th-century, with consequences visible to this day. A crucial part of US strategy during the War involved blockading Mexican ports, particularly Veracruz. These actions were commissioned to the Home Squadron, the US Navy fleet assigned to the Gulf of Mexico and the Caribbean. One of the vessels in the Squadron was the USS Somers (Figure 3), a brig-of-war 100 feet (30 m) long, 25 feet (7.6 m) wide, and with a hold depth of 11 feet (3.35 m), propelled entirely by sail and armed with ten 32-pounder carronades.

On 8th December 1846, while chasing a ship that was trying to break the blockade of Veracruz, the Somers was surprised by a strong wind, capsized, and rapidly sank. The general bearings of the Somers’ wreck site, but not its precise location, were known since the mid-nineteenth century thanks to the accounts of some of the survivors. However, it was not until the mid-1980s that the Somers shipwreck was discovered and, during the 1990s, archaeologically recorded through a collaboration between the Mexican and US governments. Since then, the Somers shipwreck has only recently been the subject of formal archaeological studies through PAMGI.

The archaeological study of the Somers shipwreck represents an excellent case study for conflict maritime archaeology and particularly for the study of shipwreck SFP. Although we know from historical sources the ship’s structural characteristics and the general circumstances that led to its sinking and the wreck’s element distribution after its nonintrusive archaeological recording, we do not know the series of events and conditions, both social and natural, that led to the shipwreck’s current state. That is, we do not know the SFP of the Somers shipwreck. The ABM we describe here was developed to study such SFP.

2. Methods

2.1 Developing an ABM

Broadly speaking, the creation of an ABM involves three steps, which are not necessarily sequential but will naturally be modified in a process of feedback and adaptation (constituting a CAS in itself). Taking the research question as a starting point, the first step is to create a conceptual model in which all the details that will comprise the ABM are defined, including agents’ characteristics and properties, processes, indicators, and user interface features. It is useful to write these details in the form of pseudocode. This is “a midway point between natural language and formal programming language [that] can be read by anyone, regardless of his or her programming knowledge, while, at the same time containing algorithmic structure that makes it easier to implement directly into real code”. Writing the different elements of the conceptual model as pseudocode will facilitate their further programming. It is also convenient to consider from this step the inclusion of elements for model verification, that is, tools that allow easy verification that all the components and processes in the ABM’s simulation platform correspond to what is stipulated in the conceptual model.

The second step consists of programming the ABM code based on what was defined in the conceptual model. Once programmed, the ABM can be used to explore the characteristics of the CAS that has been modelled and to test hypotheses about it. The third step in creating an ABM is its validation, that is, checking that its elements or behaviours...
correspond to those of the real phenomenon that has been modelled, regarding those aspects important for our research questions. Validation can be of two types: micro validation, when the behaviours of the ABM’s agents correspond to those of real agents; or macro validation when the emergent properties correspond to real ones. Macro validation is the one of interest for our purposes since, as mentioned before, we consider the distribution of elements in the shipwreck as an emergent property. In particular, we would rely on a type of macro validation called empirical validation, where the data produced by the ABM must correspond to the empirical data derived from the observation of real phenomena, i.e., the archaeological record.

2.2 Historical sources on which the ABM is based
Given that an ABM of the Somers shipwreck SFP would naturally require a three-dimensional model of the ship, we consulted historical sources that would provide information on the ship’s nautical characteristics, crew, cargo, and artillery. This information allowed us to create a very detailed 3D model of the ship considering its structural elements and other features that, although not part of the ship as such, would have been present within it at the time of its sinking. Sources also included those that gave an account of the shipwreck and possible salvage operations. This information made it possible to adapt both the 3D model and the ABM processes, as we will detail later.

Figure 4. Line plans of the USS Somers published by Chapelle. Reprinted from The History of the American Sailing Navy: The Ships and Their Development by Howard I. Chapelle. Copyright © 1949 by W. W. Norton & Company, Inc. Used with permission of the publisher, W. W. Norton & Company, Inc. All rights reserved.
2.2.1 Nautical characteristics of the Somers

To model the nautical characteristics of the Somers, we first created a two-dimensional model from a reproduction of the original line plans of the ship published by the nautical historian Howard I. Chapelle in his *The History of the American sailing Navy: the ships and their development* (Bonanza, 1949, Figure 4). The 2D model contains precise details on the shape, dimension, and position of many of the individual elements of the ship's structure (hull, decks, gunwale), as well as its accessories (windlass, carronades, bilge pump, and stove), and its rigging (masts and sails). We then used this 2D model to create the 3D model that would be used in the ABM (Figure 5).

However, both Chapelle's plans and the 2D model created from them have some limitations, for obtaining a detailed three-dimensional reconstruction of the Somers. Specifically, a series of structural and accessory elements do not appear in these sources despite constituting fundamental parts of the ship. Some include the frames, metal lining covering the bottom of the hull and rudder blade, stanchions that supported both covers, knees, beams that supported the lower deck, chains to hoist the anchors, and the anchors themselves. Several of these elements or parts of them, particularly the metallic ones (sheathing, chains, and anchors), are indeed found in the Somers shipwreck, so it was essential to take them into account when building the 3D model.

To construct these elements, we resorted to various historical sources. For the material and dimensions of the metallic sheathing covering the hull and rudder blade, we consulted Chapelle’s book Appendix “General instructions for building a Sloop of War …” and Timoteo O'Scanlan’s *Cartilla Práctica de Construcción Naval*. From these sources, sheathing may have been made of brass or copper alloys and reached the uppermost of the ship’s water lines.

Anchors were probably of the “Old Pattern Admiralty Long Shank” type, adopted by the British navy at the end of the 18th century and in use for much of the 19th century; it is likely that US Navy ships were also equipped with them. Initially, these anchors had a square wooden stock and a ring at the end of the shank. Later, these elements were replaced.
by a tubular metal stock and a shackle, respectively. The Somers was most likely equipped with metal stock anchors; however, not having the precise historical data, we reconstructed them as wooden stock anchors in the 3D model, since this type is the one that appears in the ship’s illustration by Nathaniel Currier (Figure 3).

The chains used for hoisting the anchors are a very noticeable element in the Somers shipwreck, running through the centre from bow to stern covering almost half of the site. To determine their length in the 3D model, we referred to an article by naval historian John H. Harland, stating that it “amounted to three times the depth by soundings, at the very least 25 fathoms or a quarter of a cable, sufficient at all events for the anchor to bite the ground and leave sufficient slack to allow the vessel to drift back far enough to bring the cable nearly horizontal”.35

For the stanchions’ dimensions, we referred to the appendix of Chappelle’s book and for their location on those of the USS Constellation (1854). The knees’ shape and location were also based on the Constellation (Figure 6).

Regarding the type of ballast carried by the Somers, nothing is mentioned in the records we consulted, appearing in neither Chappelle’s appendix nor in A. F. Creuze’s Treatise on the Theory and Practice of Naval Architecture (1841).36 However, other US ships of the time, such as the corvettes Vandalia (1828) and Marion (1839) or the submersible H.L. Hunley (1863), carried pig iron as ballast,37–39 so it is reasonable to assume that this would also be the case for the Somers. The Constellation, a 1,268-ton frigate,40 carried 22,940 pounds of wrought iron as ballast.41 Assuming a very similar ratio of ballast to ship size, since Somers was 259 tons, it would have carried around 4,686 pounds of ballast, encompassing a volume of 9.68 ft³ (wrought iron density = 484 pounds/ft³), distributed along the centre of the hold.

2.2.2 Operational aspects: artillery, crew, and cargo

Details about the Somers’ artillery, crew and cargo served to add to the 3D model a number of items that are not on the line plans but were certainly on the ship and therefore would affect the shipwreck SFP. Regarding artillery, the Somers was armed with ten carronades, a type of “short cannon of lightweight and large calibre mounted on a slide and on a shaft on which it rotates vertically”.42 These types of cast iron pieces were designed for powerful short-range attacks aimed at decimating both the target ship and its crew43 (Figure 7).

Regarding the crew, line plans indicate three spaces for accommodation and meeting areas for officers: cabins, wardroom, and steerage. Sailors were housed on the same deck as the officers, although not in cabins but in the space between the aft officers’ cabins and the fore storeroom. The anchor chains should also have been located in this same area. Regarding the distribution and use of spaces inside the Somers, a sailor who visited the ship at the beginning of 184343 mentioned in a newspaper article that there was

“[...] nothing to make the officers’ quarters but a long trunk house, or companion, raised a few feet from the deck, to let light and air in below, such as you may have seen in our smaller packets which ply along the sea board. [...] The officers’ quarters and the cabin are on the same floor with the berth deck of the crew, separated only by bulkheads, [...] the hold might be so occupied by stores, ammunition, ballast, and the numerous necessaries of a ship of war in actual service …”

The line plans also show three storage areas: the hold located on the bottom of the hull, which included the magazine; the fore storeroom on the lower deck, which served as a store for spare tools and equipment; and a small area behind the captain’s cabin, although it is not clear if this space actually served as a store since its dimensions were quite small (Figure 8).
Regarding the cargo that the Somers would have carried at the time of sinking, the main historical source that would have allowed us to know the details in this regard, the ship’s log, was obviously lost during the wreck. For this reason, the closest possible approximation to these details was based on secondary information provided by other social actors present during the blockade of Veracruz in 1846. All information on the movements of the fleet used to be recorded in the ships’ logs, particularly in those of the flagships from which Commodores Conner and Perry dispatched, the frigate Raritan and the steamer Mississippi, respectively. As part of PAMGI’s activities in 2019, the logs of both ships were obtained from the US National Archives. The 12th August 1846 entry of the Mississippi log details the number of provisions sent on board the Somers on that day. Additionally, the description of the Somers’ wreck written by ship’s doctor John H. Wright, originally published in The Daily Picayune newspaper in New Orleans on 22nd December 1846, also mentions some of the provisions on board the ship at the moment of its sinking. From these data, we estimate that in mid-August 1846 the Somers had in the cargo area at least 25 barrels, 5 boxes, 2 kegs, and 40 gallons of provisions; in addition to 140 fathoms (approximately 234 metres) of cables. Although these elements were not part of the ship’s structure, they were also inside when it sank and must therefore be taken into account as part of the shipwreck SFP.

2.2.3 Wreck event and salvage operations
We consulted various US and Mexican newspapers of the time that reported about the sinking of the Somers or subsequent events related to the survivors. Among those reviewed, the main sources of information were two first-hand accounts of the shipwreck. The first was sent by Captain Semmes to Commodore Perry two days after the accident,
who in turn forwarded it to Secretary of the Navy John Y. Mason. The correspondence was published on 2nd January 1847, in the Washington D.C. newspaper *Daily National Intelligencer.*20 The second, longer, account was the one already mentioned written by the ship's doctor Wright, first published in the *New Orleans Daily Picayune*28 and republished later in other newspapers.

In these documents, we looked for mentions about:

1. Parts of the ship or accessories present during its operation and sinking process that may have been removed either intentionally or as a result of the sinking, before reaching the seabed. In Muckelroy’s model, this corresponds to material floated away as a result of the wrecking process. In Gibbs’ model, these types of removal actions are found in the pre-impact warning and impact phases.

2. Salvage operations of objects from the wreck. In Muckelroy’s model, they correspond to the salvage operations sub-process. In Gibbs’ model, these types of operations, whether opportunistic or systematic, are found in the rescue and post-disaster phase.13

Regarding the first point, in the accounts of the accident given by Captain Semmes and Doctor Wright, there is no mention of jettison, i.e., heavy objects being thrown overboard, as part of the actions taken in the pre-impact alarm phase. Instead, these sources do report actions taken during the impact phase that would have involved the removal of objects during the sinking process. These actions were:

- attempts were made to loosen the sails, and cut rigging and masts, but without success
- some boxes and hatches or skylights were lost
- the boat was used

This implies that the 3D model of the *Somers* used for the ABM should:

- include all major and minor structural components of the ship
- include all the barrels mentioned above, located in the cargo area
- not include the boat

3. Results

Although the original theoretical models proposed by Muckelroy and Gibbs have been discussed and extended by other authors, we decided to use them as a starting point on which to base the conceptual model for the *Somers* ABM we present here. In subsequent works, this model will have to be extended to contain other elements and theoretical proposals as necessary, as we will discuss further on.

As aforementioned, a conceptual model defines in detail the various elements that will make up the ABM: agents and individual properties, procedures (rules of action and interaction of the agents), as well as indicators used as output variables to analyse the model’s results. Both Muckelroy and Gibbs’ models of shipwreck SFP naturally have in common the agents involved and the environment in which they interact but differ in the number and type of sub-processes involved and, therefore, in how these sub-processes affect the objects within the shipwreck. The different elements that make up our conceptual model can be generally grouped into 1) agents, 2) global variables, 3) processes, 4) indicators, 5) degradation and deposition sequences, and 6) user interface. We describe each of them in the following sections.

3.1 Agents

An agent can be defined as any “autonomous individual or object with particular properties, actions, and possibly goals”.5 Agents interact in a simulation environment in an adaptive manner, since their interactions can change as a function of time and/or the exchange of information. This results in agents being able to update their internal condition or take additional actions. Given the characteristics of the phenomenon under study, we consider that the best way to approach it would be to develop the ABM in a 3D format so that all the agents have X, Y, and Z coordinates.
Our ABM is comprised of two groups of agents. “Static” agents are those that simulate the environment, including water and the seabed, meanwhile “dynamic” agents simulate the elements of the ship, sediment, and marine organisms. It should be clarified that this classification does not refer to the nature of the agents in an archaeological context, since the marine environment is obviously very dynamic. It merely refers to the behaviour of the agents within the ABM or simulation platform, since both the volume that would surround the ship (representing the water) and the one representing the seabed, do not move. All agents, whether static or dynamic, have common characteristics including spatial location and scale. However, according to the nature of the objects they represent, they also have individual attributes which are detailed later.

Another type of agent is also present in the ABM, one we could call the “invisible agents”. These are all the people who interacted at some point in the SFP process through their actions and decisions. Although these agents would not appear in the simulations, they are represented in the ABM through the effects of said actions, which are included as options for the initial configuration of the simulation process (see the User interface section below).

Regarding dynamic agents, those that share common characteristics can (and should) be distinguished and grouped in the ABM as families or classes, using a hierarchical system based on shared attributes and procedures. This type of hierarchy and categorisation greatly simplifies programming the ABM and makes it more efficient. Once the general classes of agents have been defined, the individual agents corresponding to each one are generated, inheriting the attributes and procedures of their class while specific attributes and procedures can be assigned to each individual agent. Thus, in the ABM, we use the following classes to distinguish the groups of dynamic agents to be included in the simulation. The first class is the agents that make up the ship, whose class corresponds to the material with which the agent they represent was made: wood-oak, wood-pine, metal-iron, metal-brass, and mixed, the latter being those with combinations of materials such as oak-iron and pine-brass. Later we specify how we defined the materials for each piece and object of the ship. Additionally, there are the sediment and “coral” classes of agents.

All agents, both static and dynamic, have density and mass as common attributes. Density is assigned according to the material the agent is supposed to be made of (wood, metal, sediment, or coral). Meanwhile mass results from multiplying the assigned density by the agent’s volume. The following sections detail how these, and other individual attributes, are specifically assigned according to the elements they will represent.

### 3.1.1 The environment: water and seabed

Sea water is represented in the ABM by the entire 3D environment. It includes attributes of salinity and density that affect various processes; these attributes are defined as global variables to which all agents have access (see Global variables section). The seabed is located at the bottom of the “world”, simulating the natural context where the ship was deposited immediately after sinking.

In the Somers case, our ABM starts with the ship already settled on the seabed, that is, the model does not take into account the transit from the water surface to the bottom. Although this transit could certainly have altered the distribution of elements of the ship, in this first version of the model we assume that such alteration was minimal and only affected some minor accessory elements, not the structural elements and major accessories (equipment, artillery). In this sense, we assume that what could most alter a ship’s disposition in the transit from surface to bottom would be the listing process, which is considered in the initial conditions of the simulation and detailed later.

Among the data that has been produced by PAMGI, we have a highly detailed bathymetric survey of the site, produced with a multibeam sonar unit. However, since the postprocessing of this data is currently being undertaken, for the ABM process we assumed a completely flat seabed, without slope. It is very likely that this assumption is not entirely true since the shipwreck site is located a few hundred metres from a reef, so there is surely a certain slope; however, this is barely noticeable when diving at the site. Even so, the slope is an important aspect to consider in the SFP, since it will affect both the dynamics and interactions of natural and cultural elements, as well as the site’s element distribution. Therefore, this sea bottom setting will need to be modified in a future version of the ABM based on site-specific bathymetry.

To simulate bottom sediment movement and allow for the formation of scour pits, the bottom surface should create a random number of individual sediment-class agents. Scour pits are depressions in the seafloor that result from sediment being eroded by waves and currents after the introduction of an object to the seabed (e.g., a shipwreck). Sediment attributes are described in Sediment section. The effective formation of scour pits would serve to verify the proper functioning of the ABM, particularly the processes controlling the movement of sediments and currents. In this sense, the appearance of scour pits itself could be considered another emergent phenomenon of the CAS, which arises from the interaction between its mobile (sediment, dominant current, tides) and fixed (ship) elements.
3.1.2 The ship

As aforementioned, we used the 2D model of the Somers as a template for creating a 3D model. For some elements that do not appear in the 2D model, we used other historical documents or images from extant historical ships, such as the USS Constellation. In all cases, the layers of the 2D model or images of the historical documents were imported into Rhinoceros 6 (Robert McNeel & Associates; RRID:SCR_014339) and from each two-dimensional element shown in them, we built three-dimensional objects (Figure 9). This resulted in a 3D model of each element of the ship. The complete 3D model of the Somers can be viewed at https://skfb.ly/o76r8.

To each of the ship’s constituting elements (agents), we assigned the attributes: piece, density, mass, element-category, salvage-value, salvage-difficulty, and degradation-percentage.

The piece attribute is merely used to identify each of the ship’s elements and to access them individually. As mentioned before, we assigned the density attribute according to the material they represent. In 19th-century sailing ships, different types of wood were used for different parts depending on the required structural needs. Harder woods, such as oak, were generally used in the parts of the ship more exposed to impacts or those withstanding greater structural stress, such as the keel, stem, sternpost, or frames. Parts subject to relatively less stress, such as linings or covers, were made of softer woods like pine. For the ABM, the agents’ density value should ideally be assigned according to the specific type of wood.
from which the pieces they represent were made. However, in the case of the Somers, we currently do not have specific information on these construction details.

The closest shipbuilding material details to the Somers we have found come from Chapelle’s book Appendix, containing the specifications for the construction of the sloops-of-war Warren and Falmouth. Oak wood is specified for the different pieces of the bottom of the hull, bow, and stern, and pine wood for the remaining structural elements of the ship. Based on these data, in the ABM we assigned the density values of wood agents as follows:

- Agents representing pieces of the bottom (keel, false keel, keelson), the bow (stern foot, stem, counter stem, cutwater), stern post, rudder blade, frames, beams, stanchions, and knees were considered to be made of American white oak (live oak), which has a density of 770 kg/m³.
- Agents representing decks, masts, yards, external and internal planking of the hull, escutcheon, and all minor structural elements, were considered to be made of yellow pine wood (heart pine), which has a density of 420 kg/m³.

However, since wood density increases when becoming saturated with water, these values should be higher in the simulation. Although we do not have precise data on density change in oak and pine, a recent study with acacia wood showed that, when saturated with water, its density is 8-10% higher than when dry. Based on this data, for the ABM we considered that wood is already saturated at the beginning of the simulation, so we increased the density value of agents representing wood by 10%. Thus, agents simulating oak have a density of 847 kg/m³, and those simulating pine of 462 kg/m³.

Regarding metallic elements, we don't have specific data on the Somers. However, in his Treatise on the Theory and Practice of Naval Architecture (1841), A. F. Creuze mentions that on 19th-century ships the fittings and trim were generally made of iron and sometimes copper. The nails used to fasten the linings were usually made of copper, zinc, or tin alloy. Timoteo O'Scanlan also mentions in his Diccionario Marítimo Español (1831) that the straps (rings to hold various pieces together as in the masts) are made of iron. Finally, Chapelle’s Appendix mentions that the chains carried by Warren and Falmouth were made of iron and the hull sheathing was made of copper.

Conversely, Creuze’s mention that the nails were not made of pure copper but of an alloy of zinc, copper, and tin may suggest the use of naval brass. Additionally, the Somers was armed with 32-inch carronades. Both these artillery pieces and the bullets they fired were made of cast iron.

Considering the above, for metal agents, we assigned the following materials and densities:

- Minor pieces (fittings and mouldings), chains, anchors, and carronades are cast iron with a density of 7800 kg/m³.
- Hull sheathing is naval brass with a density of 8410 kg/m³.

The mass attribute of each agent is calculated at the beginning of the simulation from its density and volume. In case the simulation platform to be used does not have an integrated physics module, the mass would have to be calculated with the equation, $m = \frac{\delta}{C} \times V$, where $m$ is mass in kilograms, $\delta$ is density in kg/m³ and $V$ is the volume in m³.

For both the Muckelroy and Gibbs models, it is important to characterise the different ship components in terms of the ease with which they can be removed, and the value imputed to them. These two characteristics are directly related to the removal process, by flotation or salvage operations, and to the rearrangement process by current movement. For example, in the event of a warship sinking, contemporaneous salvage operations would be more likely to be undertaken for recovering artillery, ammunition, or anchors than toolboxes. Similarly, it would be easier to try to salvage minor structural elements or accessories, such as anchors, than major structural elements, such as beams.

For characterising elements in the Somers 3D model, we based our characterisation on that proposed by Gibbs in table 1 of his 2006 article. This element characterisation was the basis for assigning the values of element-category. The latter is a nominal categorical variable with four possible values: 1 = cargo, 2 = fixtures, 3 = minor structural, and 4 = major structural. Element-category, together with the material, was the basis for assigning the values of another two attributes: salvage-value and salvage-difficulty. The values assigned to these attributes for each element of the 3D model can be found in Table 1.
<table>
<thead>
<tr>
<th>Category</th>
<th>Materials</th>
<th>Elements in the 3D model</th>
<th>Material</th>
<th>Salvage value (1=low, 2=medium, 3=high)</th>
<th>Salvage difficulty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cargo and contents</td>
<td>Non-fixed items not associated with the mechanical operation of the ship and which were meant to be removable, including the ship's boats and life rafts.</td>
<td>Cargo boxes 1</td>
<td>Wood</td>
<td>2</td>
<td>= (element category \times mass) / Z coordinate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Toolboxes 1</td>
<td>Wood/metal</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ammunition boxes 1</td>
<td>Wood/metal</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Boat 1</td>
<td>Wood</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Scuttles 1</td>
<td>Wood</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Fixtures and fittings</td>
<td>Minor fixed items, fittings, yards, chains, ropes, anchors and cannon, minor mechanical items, and equipment.</td>
<td>Rigging (standing and running) 2</td>
<td>Rope</td>
<td>2</td>
<td>= (element category \times mass) / Z coordinate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sails 2</td>
<td>Cloth</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Anchor chains 2</td>
<td>Metal</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Anchors 2</td>
<td>Metal/Wood</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Windlass 2</td>
<td>Wood/metal</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Carronades and carriages 2</td>
<td>Metal/Wood</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pump 2</td>
<td>Metal/Wood</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stove 2</td>
<td>Metal</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>
Table 1. Continued

<table>
<thead>
<tr>
<th>Category</th>
<th>Materials</th>
<th>Elements in the 3D model</th>
<th>Element category (1=cargo, 2=fixtures, 3=minor structural, 4=major structural)</th>
<th>Material</th>
<th>Salvage value (1=low, 2=medium, 3=high)</th>
<th>Salvage difficulty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor structural</td>
<td>Items not normally removed, but whose removal would not compromise the integrity of the hull, such as bulkheads, decks, masts, superstructure, major mechanical items, and equipment.</td>
<td>Decks 3 Wood 1</td>
<td>= (element category × mass) / Z coordinate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hatches 3 Wood 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gutteres 3 Metal 1</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td>Hawseholes 3 Metal 1</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Masts 3 Wood 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Deadeye chains 3 Metal/ Wood 1</td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td></td>
<td>Rudder blade 3 Wood 3</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Mast fittings 3 Metal 1</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Portholes 3 Wood/ metal 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Rail mouldings and steps 3 Wood 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bulkheads 3 Wood 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stairs 3 Wood 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Major structural</td>
<td>Elements of the ship whose removal would affect the integrity of the vessel, including hull planking, ribs, and other structural items.</td>
<td>Frames 4 Wood 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Beams 4 Wood 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stanchions 4 Wood 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Knees 4 Wood 1</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>External and internal planking 4 Wood 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rails 4 Wood 1</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Escutcheon 4 Wood 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Metallic sheathing (hull and rudder blade) 4 Metal 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

First two columns taken from Ref. 13.
The salvage-value attribute is a continuous numerical variable whose initial values were assigned to each agent arbitrarily. We assumed that, similar to the previous example, artillery, ammunition, or some equipment would be more valuable for salvaging than structural elements. However, they may be modified at any time. Values could be 1 representing a “low” salvage value, 2 a “medium” value, and 3 a “high” value.

The salvage-difficulty attribute is also continuous and numerical. To assign the initial values, we made the following assumptions:

• It would be easier to salvage mobile elements than structural elements of the ship. Therefore, mobile elements have lower salvage-difficulty than structural elements.
• It would be easier to salvage items higher up (closer to the surface) than lower down. Therefore, elements with a lower Z coordinate value have less salvage-difficulty than those with a higher Z coordinate value.
• It would be easier to salvage light items than heavy ones. Therefore, salvage-difficulty is also a function of the object’s mass.

Thus, the initial value of each agent’s salvage-difficulty is given by the following equation:

\[
salvage\_difficulty = \frac{(element\_category \times mass)}{Z\_coordinate}
\]

Although initial values are assigned to the salvage-value and salvage-difficulty attributes at the beginning of the ABM, these values change as the simulation advances, depending on the degradation-percentage of each element and time. This is later detailed in the Execution section.

The degradation-percentage attribute is a continuous variable. Its initial value set to a random number between 0 and 10% for woods, and between 0 and 5% for metals. This adds stochasticity to the ABM by simulating that the pieces, due to their use, did not have complete integrity at the time of the shipwreck. Each element’s degradation-percentage increases with the simulation time according to the rules established in the Degrade sub-process. In the case of agents representing wood, when this attribute reaches a value of 100, the agent disappears from the environment, simulating its complete degradation.

### 3.1.3 Sediment

Agents representing sediment are added to the ABM at two points: 1) as part of the seafloor surface; 2) as part of the ocean current simulation process. These agents represent any type of sediment that is deposited on the site.

Similar to the bathymetric context, the ABM was designed in a speculative way regarding the sedimentology since we lack data about the specific sediment composition where the Somers was deposited after sinking (near Isla Verde reef) or the sediment that has been covering the wreck since then. This sedimentological characterisation will be part of the next activities by PAMGI. The closest information we have found about such sedimentary composition refers to the Hornos Reef, also in Veracruz. Between 1 and 2 m deep, the sediment is composed of fine (0.125 mm) to coarse (1 mm) sand. However, this data cannot be taken as similar to that of the Somers wreck for two reasons: 1) Hornos Reef is located four kilometres northwest of Isla Verde; 2) the Somers shipwreck is 30 metres deeper than the site where the Hornos Reef samples were taken.

In the coming months, PAMGI will conduct a very detailed marine-geological survey at the Somers’ site to provide us with enough data to produce a comprehensive understanding of the sedimentary processes over time for this specific shipwreck. A future version of the ABM will also include real data from the context, allowing us to produce more realistic simulations, contrast both model versions, and produce a deeper understanding of the ABM’s powers and limitations.

Therefore, for this first version of the ABM, we randomly assigned the value of the agents’ size attribute representing sediment, between 0.00002 and 0.002. Since the unit of distance in the ABM is the metre, these values mean that the smallest particle size is 2 microns and the largest is 2 mm. This random assignment results in a proportional size distribution that represents a silt-sandy sediment (sand = 2.0–0.05 mm; silt = 0.05–0.002 mm). Considering this type of sediment, we assigned 1265 kg/m³ (silty sand) as the density attribute of these agents. These values, like all others in the ABM, can be later modified when specific data on the sedimentary composition of the Somers shipwreck become available.
3.1.4 Corals

Biological colonisation is very common in marine archaeological contexts, particularly in those with metallic elements that serve as support for colonising organisms. However, this colonisation differentially affects metals, being abundant, for example, in iron objects and almost non-existent in those made of bronze. In contrast, submerged wood can also be subject to colonisation, but this is not usually observed in submerged archaeological contexts since the degradation of said material by boring organisms is usually faster than the growth of colonisers.49

Characterisation of the colonising organisms in the Somers shipwreck has not yet been carried out; this is also one of the next PAMGI activities. However, it is possible to appreciate the great variety of marine flora and fauna in the wreck (Figure 10). In a study on biological colonisation where iron and brass discs were submerged in a similar environment, the waters of Campeche, Mexico, authors found 53 different species on the surface of the discs. Colonisers fell into five categories: 1) organisms with vertical growth, including filamentous macroalgae and bryozoans; 2) encrusting organisms such as sponges, particularly abundant on the iron surface; 3) calcareous tube-forming organisms such as polychaetes; 4) bivalves such as oysters; 5) conical exoskeleton organisms, such as barnacles.50

The ABM includes only one type of agent that represents colonising organisms. We collectively named these “corals” and their initial-size is 0.0005. This corresponds to 0.5 mm since the “size of settling larvae usually does not exceed 1 to 2 mm and often is below 0.5 mm”.51 A study on the biomass of different species of colonising organisms sampled in coral reefs of the Mexican Caribbean reported an average biomass density of 12 mg/cm².52 We used this data to assign the coral agents a density of 0.0012 kg/m³ (assuming the samples in that study were 1 cm tall). In To adhere/grow corals section, we define the process of adhesion and growth of coral agents.

3.2 Global variables

Global variables are those common to the entire model, which all agents can access to carry out processes. In the Somers ABM, global variables include gravity, the salinity and density of the seawater, the direction and speed of the sea currents, the simulated month and year, and the salvage moments. Almost all of these variables are used by agents to compute different processes as described below.

The force of gravity in the ABM corresponds to the acceleration with which the objects will “fall” i.e., change their position with respect to the Z-axis. The value assigned to this variable is 9.81 m/s², which corresponds to the gravitational pull at sea level. It should be clarified that the final falling speed of objects is not only a function of gravitational attraction but also of their mass, volume, and resistance given by water density so the speed must be calculated as part of the movement process.

The salinity and density of seawater are also defined as global variables. Various authors have reported salinity values for different points of the Veracruz Reef System, ranging from 33.6% to 38%.46,53–55 Based on these data, we assumed an average value for the global salinity variable of 35%.

Figure 10. Metallic object, probably the sheave of a pulley,71 surrounded by colonising organisms in the Somers shipwreck. Even in such a small space (approximately half a metre), the great variety of biological colonisation can be appreciated. Photo: Emilio Vélez Quintero, 2018, courtesy of the author.
On the other hand, seawater density is a function of both salinity and temperature. According to our own data obtained by scuba diving in different points of the Veracruz Reef System, including the Somers shipwreck, the water temperature below 20 m depth remains around 23 °C regardless of the season (dry or rainy). Considering this temperature and a salinity of 35%, the seawater-density in the ABM is 1024 kg/m³.

The current-direction and current-speed global variables are defined for the different months of the year based on the measurements made in Isla Verde by Salas-Pérez et al. Their measurements covered the entire water column at the sampling sites and are reported as vertical averages, therefore, we considered them adequate for the ABM in which the interactions will take place at the seabed level. Although the unit of distance at sea is the nautical mile (equivalent to 1852 metres or a minute of arc on the compass) and the speed unit is the knot (nautical mile/h), for the ABM we decided to keep units in km/h for consistency with those reported by Salas-Pérez et al. For the spring months (April-June) current direction flows towards the NW at 0.37 (± 0.40) km/h (mean ± s.d.). In summer (July-September) the direction is towards the SW at 0.24 (± 0.36) km/h. In autumn (October-December) the current goes to the NE at 0.26 (± 0.40) km/h. During the winter months (January-March) it flows to the SE at 0.84 (± 0.28) km/h.56

These values are not constants in the ABM. A random-normal function is used to produce normally distributed float random numbers, with the specified mean and standard deviation. In this way, each time the current direction and current speed variables are used, their values change within the range of the real measurements. For this reason, these two variables, unlike the rest of the global variables, are not assigned at the start of the simulation.

The current-month and current-year are also defined as global variables that determine, respectively, the month and year being simulated. Its initial values are “December” and “1846” corresponding to the date the Somers wrecked. How these variables are treated is specified later, in Time section.

Finally, the global variable salvage-moments determines the moments of the simulation in which the Salvage sub-process is executed (see To salvagesection). The values for this variable are stored in a list and are generated randomly with the maximum possible value being 2064, the number of months that make up the 172 years that passed from the Somers shipwreck until 2018 when the archaeological record of the site was carried out by PAMGI.

3.3 Processes (rules of action and interaction)
There are two major “moments” in the design and operation of an ABM: 1) “setup” when the user establishes the general parameters on which the simulation will be based i.e., the system’s initial conditions; and 2) “run” when the processes are executed. These two moments are designed and implemented in the two major processes of the ABM that we call Configuration and Execution. Figure 11 shows a flow chart of the ABM, including the processes and operations of both moments.

3.3.1 Configuration
3.3.1.1 Create seabed
The first sub-process in the simulation’s setup defines the area that will represent the seabed and its attributes. The seabed is located at the bottom of the world, immediately adjacent to the ship's bottom. As mentioned previously, agents representing the seabed must create a random number of 1 to 10 sediment-class agents on each centimetre of their surface, which will allow simulating the movement of the bottom sediment and the formation of scour pits.

The pseudocode [1] for this sub-process is:

- Locate seabed
  - seabed Z-coordinate = false keel Z-coordinate
- Ask seabed agents
  - create between 1 and 10 sediments on every centimetre of their surface

---

1As aforementioned, pseudocode does not refer to a formal coding language. It is rather “a midway point between natural language and formal programming language [that] can be read by anyone, regardless of his or her programming knowledge, while, at the same time containing algorithmic structure that makes it easier to implement directly into real code”.

---
3.3.1.2 Load ship
In this sub-process, the 3D models that make up the parts of the ship are imported into the simulation environment. Although the geometry of the 3D models is made up of vertices and edges that form meshes of triangles, in the simulation each part of the ship constitutes an individual agent. Therefore, the behaviour of the agent must occur at the level of the complete mesh that makes it up and not at the level of the individual vertices or edges that make up the said mesh.

Immediately after loading each piece, the class of agent to which it belongs is assigned, so that it already has the corresponding attributes. As mentioned before, the density and mass values of each agent depend on the material they represent. As part of this sub-process, density is first assigned to each agent and based on this and its volume, mass is calculated. Subsequently, initial values of each of the attributes that are specific to the agent are assigned.

3.3.1.3 Set global variables
In this step, the initial values of the different global variables are assigned. The pseudocode for this process is:
Establish

- gravity = 9.81
- salinity = 35
- seawater-density = 1024
- current-month = 12
- current-year = 1846
- current-direction = NW-->SE
- current-velocity = random-normal with mean = 0.84 and s.d = 0.28
- salvage-moments = choose n (n = total-salvages) between 1 and 2,076

3.3.2 Execution

Once the simulation’s initial conditions have been established in the Configuration process, we next define all those sub-processes that will imply actions and interactions between the agents. These sub-processes are included in the process called Execution.

As mentioned in Shipwreck site formation processes section, Muckelroy’s model considers three types of sub-processes: 1) those that remove elements from the system (extracting filters), including the shipwreck event, salvage operations, and the disintegration of perishable objects; 2) those that alter the spatial arrangement of objects (scrambling devices), including the shipwreck event and seabed movement; and 3) deposition of materials, including sediments and marine life. Conversely, Gibbs’ model considers the same general processes but makes them more specific and detailed, emphasising the decisions behind the actions. For example, in Muckelroy’s model, salvage operations constitute a single sub-process, but are subdivided in Gibbs’ model into crisis salvage, survivor salvage, systematic salvage, and opportunistic salvage.

Based on the above, in the Execution process of the Somers ABM, the series of actions (sub-processes) that are executed at each simulation moment are: 1) to salvage, 2) to degrade, 3) to grow corals, and 4) to move (simulating both movement and sediment deposition). Since all processes involve actions in time, we first need to define time in the ABM.

3.3.2.1 Time

In an ABM, the Execution process (with all its sub-processes) can be executed once or repeated cyclically. This last case is the most commonly used when modelling complex systems since it allows agents’ actions and interactions to be simulated iteratively over time. Thus, each iteration of Execution represents a unit of simulation time. Time units are arbitrarily defined according to our research questions and can represent real units (seconds, hours, years) or be dimensionless.

To determine the amount of time each Execution cycle would represent in the Somers ABM, we considered the units used to report the data we used for defining the different sub-processes. Thus, data about the movement of marine currents were reported by the seasons of the year i.e., quarterly, while studies on wood and metal degradation, as well as on the growth of colonising organisms, reported data at intervals of six months or one year. Based on this, we decided that the unit of time that would represent each moment of Execution in the ABM would be one month.

From this definition of time, we needed to adjust the mentioned data to said time unit. In the case of the sea current during the summer months, for example, it was reported to flow in a SW direction at an average speed of 0.24 (± 0.36) km/h. Therefore, it was necessary to convert these current velocity data to metres per month.

A problem that can arise when using units of time such as a month is that the movements of the elements in a single iteration of the ABM can be very large. For example, 0.24 km/h would imply a displacement of 173 km in a month. To avoid this problem, we programmed the ABM so that the salvage, degradation, and organism growth sub-processes (see below) stop whenever something is moving, and resume when movement stops. The latter is calculated as a differential between the position of every element at the beginning and the end of the iteration.
From the above, it follows that the ABM should be able to keep a record of the month to which the Execution cycle that is running at a given moment corresponds. The global variable current-month is used for this purpose, which has values from 1 (January) to 12 (December), and in each iteration of Execution increases by one unit (returning to 1 after 12). Additionally, the global variable current-year keeps track of the year being simulated and increases one unit each time the month changes back to “1” (January). The initial values of current-month and current-year are “12” (December) and “1846”, respectively, corresponding to the date the Somers sank.

Furthermore, to be able to analyse the SFP after a specific time has elapsed, the variables end-month and end-year are used to define the date on which the simulation should end. The default options are defined for August and 2018 so that the simulation covers the time passed from the shipwreck until the photogrammetric record of the wreck was carried out by PAMGI59; however, the user can modify both values. The simulation stops when it reaches the dates set in these parameters.

The pseudocode for time-related actions is:

Before simulation starts (SETUP):

- set current-month = 12
- set current-year = 1846

On every Execution:

- if current-month < 12, set current-month = current-month + 1
- if current-month = 12, set current-month = 1
- if current-month = 1, set current-year = current year + 1
- if current-month = end-month AND current-year = end-year, stop the simulation

3.3.2.2 To salvage

This sub-process simulates both contemporary and post-wreck salvage operations. In Muckelroy’s model and even more so in Gibbs’ model, salvage events are central to shipwreck SFP as they have the potential to significantly alter the distribution of objects observable in the archaeological context. That is, to generate great differences between the systemic context and the archaeological context. In Muckelroy’s model, all these actions are grouped into the salvage operations sub-process. In Gibbs’ model, contemporary salvage operations fall into the first three categories of crisis salvage, survivor salvage, and systematic salvage; while subsequent operations fall into the fourth category, opportunistic salvage.

Unlike the previous processes in the ABM where user input is minimal, this sub-process relies heavily on the information the user enters before starting the simulation. This information necessarily comes from historical research about the number of salvage operations that have been carried out on the wreck, from its sinking to the present day. Of the four types of salvage operations proposed by Gibbs, at least the first three should leave some kind of historical record, which may be as diverse as survivors’ accounts, ship's logs, official documents issued by those responsible for the ship or the fleet (captains, commodore), newspaper notes, paintings, literary works, or photographs. The fourth type of operation, opportunistic salvage, is much less likely to leave a historical record as these operations are often the result of illegal salvage, the recovery of objects by local inhabitants, or recreational divers. However, it is possible to have data on this type of operation, which is why they are also considered in the ABM.

For the simulation to take into account the four types of salvage operations, we included selectors for each of them in the user interface. These are:

- number-of-salvage-operations-during-the-crisis
- number-of-salvage-operations-by-survivors
number-of-systematic-salvage-operations

number-of-opportunistic-salvage-operations

If the user knows these numbers from historical data, the number of corresponding salvage operations can be determined in each selector, with options ranging from 1 to 10. Additionally, we included a random number option (limits 0 and 10) in each selector to be able to simulate different scenarios when the exact number of salvage operations is unknown. In the case of the Somers, for example, the documents we have consulted so far do not mention any salvage operation being carried out contemporary to the sinking, so the initial values of the first three selectors would be zero.

Being able to distinguish between types of salvages allows archaeologists to have greater precision in the story we tell about the SFP since both the motivations behind the salvages and the potential number of objects removed will be different in each salvage type. However, for simulation purposes we considered all salvage operations to be equivalent in terms of the number of objects removed from the environment as a result of each operation. In other words, in the ABM, as many objects can be lost from a systematic salvage operation as from an opportunistic one. This assumption is not necessarily true in historical terms, but we made it so for the sake of simplifying the ABM.

Therefore, for this sub-process, the total number of salvage operations carried out on the wreck from its sinking to the present is of interest. This number is stored in a global variable named total-salvages, the result of adding the values of the four selectors described above. It is defined after the initial setup of the environment but before the start of the simulation. Since each time step of the ABM corresponds to a month, the Salvage sub-process should not be executed in each iteration because it would imply that salvage operations would have been carried out every month since the sinking, which would be a mistake. Instead, the sub-process should only be executed at certain moments, whose total number would be defined by the total-salvages variable, throughout the simulation. To determine at what times the sub-process runs, a list of all possible moments is created, and the number of times is selected randomly.

Given that, according to Gibbs' model, crisis salvage operations, survivor salvage, and systematic salvage are contemporaneous with the shipwreck event, the salvage moments corresponding to these three variables occur in the first 24 months. Consequently, this simulates that these operations would have taken place between the years 1847 and 1848, that is, during the Mexican-American War. In contrast, the moments corresponding to opportunistic salvage can occur in any month from January 1849 to the end date of the simulation, with a maximum value of 2,064, the number of months in the 172 years elapsed from the sinking of the Somers to PAMGI's recording. The values of the months in which salvage operations are to be simulated are stored in another global variable called salvage-moments.

The salvage-moments variable is calculated immediately after total-salvages so that its values are already set in the global variable when the simulation starts. The execution of the Salvage sub-process occurs when current-month is equal to one of the numbers in the salvage-moments list.

Therefore, to simulate the loss of objects due to salvage operations, when the Salvage subprocess is executed, a probability of disappearing from the environment is calculated for each piece of the ship, which is directly proportional to its salvage-value (SV) and inversely proportional to its salvage-difficulty (SD). The result of dividing these two values (SV/SD) is normalised by dividing by the maximum value of SV/SD of all the agents so that it constitutes a probability value, i.e., a positive number between 0 and 1. For each piece, this number is stored in a local variable called the disappearance-probability. Thus:

\[
\text{disappearance\_probability} = \frac{\text{SV}}{\text{SD}} \frac{1}{\max \text{SV} / \text{SD}}
\]

In the case of the Somers, something that would undoubtedly have challenged salvage operations in the months or years following its sinking and until the middle of the 20th century, was the depth at which the wreck is located (32 m). But that difficulty has lessened considerably since the mid-1940s with the invention of scuba diving equipment by Cousteau and Gagnan in 1942. To take this into account, when the current-year value reaches 1950, the salvage-difficulty value of all agents is reduced by 50%. This percentage is arbitrary but can be changed at any time.

Finally, to increase stochasticity and simulate in a certain way the possible success or failure of the rescue operations, if an agent’s disappearance-probability is greater than 0.5, a new local variable named disappearance-success with a random value between 0 and 1 is calculated. If disappearance-probability is greater than disappearance-success, then the piece disappears from the environment. This implies that, even when the simulation of a salvage operation is programmed and
the sub-process executed, it does not necessarily result in an agent’s disappearance, since the latter is a function of said disappearance-success.

The pseudocode for this sub-process is:

Before simulation starts (during Configuration):

- set the number of salvage operations on each selector
  - initial values: first three = 0, opportunistic salvage = random up to 10
- calculate total-salvages = sum of four selectors
- calculate salvage-moments
  - random up to 2,064

On every Execution:

- if current month = any of the items in the salvage-moments list, execute Salvage
  - for each agent
    - if current year \( \geq \) 1950, reduce salvage difficulty by 50%
    - calculate disappearance-probability = \( \frac{SV}{SD} \) / max SV/SD
    - if disappearance-probability > 0.5
      - compute local variable disappearance-success \( \rightarrow \) random between 0 and 1
      - if disappearance-probability > disappearance-success, remove the piece from the environment.

3.3.2.3 To degrade

This sub-process simulates the degradation of wooden elements and corrosion of metallic elements. To make it easier to verify the correct operation of this process, we divided it into two sub-processes: degrade-wood and degrade-metal.

**Degrade-wood**

Wood degradation in archaeological contexts, both terrestrial and submerged, depends on several factors including the type of wood and the time it has been in the context, as well as its particular characteristics such as moisture content, oxygen, pH, temperature, and, in marine contexts, salinity. While in most archaeological contexts microorganisms (bacteria and fungi) are the main agents responsible for wood degradation, in marine contexts with warm water conditions and abundant light, wood is rapidly degraded by boring animals long before degradation by microorganisms begins. Bivalve molluscs of the Teredinidae family, especially *Teredo navalis*, and crustaceans of the genus *Limnoria* are the main organisms responsible for drilling exposed wood. The specific prevalence of the different species of borers varies significantly depending on environmental conditions, particularly temperature and salinity. However, both in warm (16–26 °C) and cold waters (5–12 °C), these animals can completely degrade a piece of wood between six months and a year, depending on the size and type of wood.

Degradation by boring animals is limited to the exposed parts of the submerged wood and is completely absent in those parts covered by more than 10 cm of sediment. In these cases, degradation does continue, although much more slowly, due to the action of soft rot fungi, tunnelling bacteria, and erosion bacteria. Below 40 cm of sediment, conditions become almost anaerobic and the wood degradation process is drastically reduced, being carried out exclusively by erosion bacteria that can proliferate in such conditions. Therefore, the degradation of wood-representing agents in the ABM depends on whether they are exposed or covered by sediment.
Based on experimental data reported by Pournou et al., and Björdal & Nilsson, we developed the following linear regression equations for estimating the monthly degradation of oak and pine woods, both exposed and covered by sediment. A detailed explanation of how we developed these equations can be found in Ref. 70.

for oak:
\[
\text{degradation\_percentage} = (4.52 \times x - 5) \times (1 - \text{sediment\_percentage}) + \left( \frac{-0.00056 \times 0.0283}{1000} \right) \times \text{sediment\_percentage}
\]

for pine:
\[
\text{degradation\_percentage} = (8.33 \times x - 5) \times (1 - \text{sediment\_percentage}) + \left( \frac{-0.000928 \times 0.0547}{1000} \right) \times \text{sediment\_percentage}
\]

These calculations correspond to the Execution phase of the ABM. However, as mentioned previously, before the simulation starts wood agents have a degradation-percentage randomly set between 0 and 10% to add stochasticity to the model by simulating that pieces did not have complete integrity at the time of the shipwreck.

It was common practice to cover the hulls of wooden ships with metal sheets to reduce wood degradation since the corrosion products of said metals are toxic to boring organisms. Thus, the metallic sheathing conferred protection against degradation to those parts of the ship that would be permanently submerged, i.e., the bottom of the hull and the rudder blade. To simulate such protection in the ABM, in wooden elements that are in contact with brass parts, the degradation-percentage is set to only 10% of the result of the normal degradation calculation. This percentage of “protection” was arbitrarily set but can be modified at any time based on experimental data.

The pseudocode for the degrade-wood sub-process is:

Before simulation starts (during Configuration):

- set degradation-percentage = random between 0 and 10

On every Execution:

For all agents with wood:

- calculate cm-sediment = sum of the sizes of sediments and corals adjacent to the agent \times 100

For wood-oak agents:

- calculate sediment\_percentage = cm\_sediment/100
  - if sediment\_percentage > 0, calculate degradation\_percentage = (4.52 \times x - 5) \times (1 - sediment\_percentage) + \left( \frac{-0.00056 \times 0.0283}{1000} \right) \times sediment\_percentage
  - if adjacent to brass, set degradation\_percentage = degradation\_percentage \times 0.1

For wood-pine agents:

- calculate sediment\_percentage = cm\_sediment/100
  - if sediment\_percentage > 0, calculate
    - degradation\_percentage = (8.33 \times x - 5) \times (1 - sediment\_percentage) + \left( \frac{-0.000928 \times 0.0547}{1000} \right) \times sediment\_percentage
    - if adjacent brass, set degradation\_percentage = degradation\_percentage \times 0.1
Degrade-metal

The degradation of metallic objects in submerged archaeological contexts results from their interaction with the environment and colonising organisms. The former produces corrosion as a result of an electrochemical reaction that depends on the metal’s electrode potential and the medium’s pH. On the other hand, the development of colonising organisms and their concretions exert a protective effect against corrosion because, with their growth, they limit the exposure of the metal to the environment.

As we did for wood degradation, for metal elements we also developed linear regression equations for estimating the monthly corrosion of iron and brass pieces based on experimental data reported by López Garrido et al. A detailed explanation of the development of the following equations can be found in Ref. 70.

\[
\text{corrosion\_percentage} = -0.0876 + (0.914 \times \text{elapsed\_months}) + (-0.0452 \times \text{elapsed\_months}^2)
\]

for iron:

\[
\text{corrosion\_percentage} = (0.2 \times \text{elapsed\_months}) + 0.133
\]

for brass:

Corrosion of metal agents is visually represented in the simulation with a change in colour towards dark red or green depending on whether the agent represents iron or brass, respectively. As aforementioned, before starting the simulation, metals have a corrosion-percentage randomly set between 0 and 5%, simulating that the pieces did not have complete integrity at the time of the shipwreck.

The pseudocode for this sub-process is:

Before simulation starts (during Configuration):

For all metal agents:

\* set corrosion\_percentage = random between 0 and 5

On every Execution:

For metal-iron agents:

\* calculate

\[
\text{corrosion\_percentage} = -0.0876 + (0.914 \times \text{elapsed\_months}) + (-0.0452 \times \text{elapsed\_months}^2)
\]

\* if corrosion\_percentage < 0, set it to 0.

\* if corrosion\_percentage > 50, set colour to dark red

For metal-brass agents:

\* calculate \[
\text{corrosion\_percentage} = (0.2 \times \text{elapsed\_months}) + 0.133
\]

\* if corrosion\_percentage < 0, set it to 0.

\* if corrosion\_percentage > 50, set colour to green

Degrade-rigging: the great missing

Although a ship’s structure and equipment (e.g., artillery, anchors) usually occupy much of the attention during the study of a wreck, a less attractive but equally important component is all the elements that make it possible for the ship to move. These are rigging and sails.

Rigging is “the whole of all the cordage of a ship, and the title of every whole piece of rope”. In addition to the ropes, it is composed of several very diverse elements that facilitate their movement, collectively called blocks (Figure 12). Although rigging usually receives many different names depending on its location or function on the ship, we can generally speak of two types: standing rigging, the one that does not move and whose function is to provide “fastening for
masts and topmasts”; and running rigging, the one that “is in play [i.e., in motion] for the handling of the entire rig”\(^{42}\) (Figure 13).

As highlighted by Sanders in his detailed article on the characteristics of ropes and their archaeological record, a ship’s rigging was not simply an accessory but

“[…] a major part of the investment in a ship, requiring major industry to support it. […] A French frigate of 1790 required 27 km of cordage for rigging and a further 5 km for replacements. […] A late-18th-century British 74-gun ship required c.80 tons of rope to rig it, and some 922 blocks”\(^{64}\)

Although cordage and sails of ships before the 20th century were made of perishable organic materials, it is not uncommon to find remains of these elements in archaeological excavations of shipwrecks. They are often adhered to pieces of iron or covered with calcareous concretions, as complete pieces impregnated with tar or a similar compound, or as complete or fragmented pieces deposited in the sediment and very prone to disintegrate during excavation.\(^{65}\)

Therefore, models of shipwreck SFP should include at least some rigging elements. However, we decided not to include these elements nor their degradation process in the Somers ABM for two reasons. Firstly, the line plans published by Chapelle only show the dimensions of the structure, masts, and sails (see Figure 4), but do not give details about rigging. This does not constitute an omission on Chapelle’s part, much less the original author of the plans (the shipbuilder). It is simply that the rigging, both standing and running, did not require a specific plan since its quantity and dimensions were adapted according to the dimensions of the masts and sails specified in the construction plans.

---

**Figure 12. Ropes and blocks (From Ref. 71).**
An alternative for adding rigging to the 3D model of the *Somers* would be to rely on Nathaniel Currier’s lithograph of the ship (Figure 3). However, it must be considered that the rigging shown in a ship’s representation, whether pictorial, sculptural, or a 3D model, does not necessarily correspond to the totality of the rigging carried in the ship. This is due to several reasons. Firstly, “artists were seldom riggers or shipwrights, so pictures are seldom accurate. Rigging may obscure the composition and is not always aesthetically pleasing, so is only selectively portrayed. Models seldom have their original rigging, and problems of scale mean that the detail of the real object cannot be replicated. A further limitation of rigging on models is that they are representational or instructional.”

This would imply that even based on Currier’s lithograph or any other representation of a ship of the time, the 3D model of the *Somers* would not have all the elements of the rigging and its accessories. Although this constitutes a limitation, it is an inherent characteristic of all models, in that they represent only those aspects of reality that allow answering specific questions about it.

The second reason for not including rigging and its degradation process in the *Somers* ABM is that we do not have experimental data about it. The degradation of textiles in humid archaeological contexts occurs mainly by bacterial action, either mechanical (by penetration and growth within the fibres) or chemical (by enzymatic hydrolysis). In most of the studies that have analysed such degradation, textiles have been buried in various types of soils with different moisture conditions. However, such studies have included different types of fabrics, but no ropes. As far as we know,
there are no experimental studies where the rigging degradation processes have been specifically analysed, similar to those on which we relied for designing the degradation processes of wood and metals. This would be an interesting and necessary research topic to delve into the knowledge of shipwreck SFP.

3.3.2.4 To adhere/grow corals
The process of biological colonisation of submerged materials is one of great complexity and specificity between organisms, be they bacteria, algae spores, or larvae. However, in all cases it involves four main processes: 1) transport to the surface of the substrate, 2) settlement, 3) attachment, and 4) growth. Since the biological colonisation process was not this work’s subject, for the Somers ABM we simulated the first three stages (transport, settlement, and attachment) as a single “adherence” event, which was defined to be random. That is, we assigned a random probability for colonising organisms (i.e., coral agents) to appear on the surface of the agents that represent metals. In this way, for the simulation, we concentrated only on specifying the growth conditions of these organisms.

In the ABM, the biological colonisation process is limited to agents that represent metals and is differential between iron and brass. We based growth rates for both metals on experimental data reported by two studies carried out in the Gulf of Mexico.50,67 The detailed rationale for determining such growth conditions can be found in Ref. 70.

For elements representing iron, we defined that biological colonisation would advance at 1.547 cm per month, while the rate of growth on brass pieces is 2.3% of their size per month.

The pseudocode for this process is:

To simulate adherence of colonising organisms:

For all metal agents

* if they don’t have coral on top
  * “toss a coin” → if random-float (range 0-1) > 0.8, sprout a coral

  (note: this 20% probability of appearing was set this way to avoid performance problems in the simulation since it might quickly be saturated with coral agents)

To simulate the growth of colonising organisms:

For corals in iron

* if size < size of the metal-iron agent on which it is
  * set size = size + 0.01547

For corals in brass

* if size < size of the metal-brass agent it is on
  * set size = size + (size*0.023)

3.3.2.5 To move
In terms of Muckelroy and Gibbs’ SFP models, agent movement allows to simulate:

1. Object loss by flotation. In Muckelroy’s model, this corresponds to material floated away as a result of the process of wrecking (Figure 1). In Gibbs’ model, this type of removal action is found in the pre-impact warning and impact phases (Figure 2).

2. Object loss due to jettisoning. While this type of action is not considered in Muckelroy’s model, in Gibbs’ model it occurs during the pre-impact warning and impact phases (Figure 2).
3. Object deposition by gravity and sedimentation. In both Muckelroy and Gibbs’ models, material subsequently deposited on site occurs after the sinking process, as one of the scrambling devices, constitutes the natural events of site formation (Figure 1 and Figure 2).

Ideally, the simulation platform to be used should have a physics module that allows adequately simulating agents’ movement (e.g., Unreal Engine). Having this functionality greatly simplifies the programming and performance of the ABM. However, in case the platform does not have a physical movement simulation module (e.g., NetLogo), in Supplementary material we provide an alternative for encoding the movement process of mobile agents. For each agent this calculates: 1) the displacement velocities in each of the three dimensions (X, Y, and Z) as a function of current velocities and seawater density, and 2) the new position of the agent after applying said displacement velocities.

3.4 Indicators and their analysis

To be able to test historical and archaeological hypotheses we need to generate a set of indicators that would allow comparing the results of the simulations to data obtained from historical documents and the archaeological record of the wreck. As mentioned earlier, this corresponds to a model validation of the empirical macro validation type.

Next, we present some basic indicators considered necessary for testing hypotheses. These should be visible in the user interface throughout the simulation and, most importantly, they had to be exported to a text file or similar for later analysis.

3.4.1 Simulated date

We added an indicator called Simulated date to know what month and year the current moment of the simulation corresponds to, in addition to being used in other indicators. This indicator simply combines the global variables current-month and current-year.

3.4.2 Spatial distribution of shipwreck elements

The distribution of wreck elements on the seabed is the main indicator for considering the ABM validated. It is also the main output or outcome variable of the shipwreck SFP considered in both Muckelroy and Gibbs’ models (observed seabed distribution).

In terms of representation, the distributions of elements in an archaeological record can be displayed in different ways, depending on the detail required for analysis. One way is to represent them as forms, that is, presenting their contours or volumes. This is what archaeologists usually do when drawing a context in a plan or section. It is a relatively undetailed representation but undoubtedly useful for recording and interpreting contexts. Another much more detailed method is to represent the context as a continuous array of points in three-dimensional space. This type of representation is called a point cloud and is the kind that results from a topographical survey or a photogrammetric record, for example.

In the case of the Somers wreck, from the photogrammetric record carried out by PAMGI in 2018, a very dense point cloud was obtained that represents the distribution of wreck elements in great detail (Figure 14). In the ABM, to compare the results of the simulations with said photogrammetric record, it was necessary to obtain a point cloud from the simulation. Points are given by each of the vertices that make up the 3D meshes of the elements of the wreck. These points are obtained by exporting the data of the coordinates of all vertices (i.e., their positions in X, Y, and Z) of all remaining agents at the end of the simulation to a comma-delimited text file.

The pseudocode for this export process is:

- create CSV file in a user-defined location
- from each remaining agent’s mesh, obtain each vertex ID and position
  - write ID, X, Y, and Z of vertices in the text file

From the above it follows that we should then be able to compare two point clouds, the one obtained from the simulation against the one from the archaeological record. For this, a number of open-source tools are available (e.g., CloudCompare) that would yield the differences between point clouds both visually and numerically by calculating a correlation value between them. Based on these data it would be possible to 1) decide whether the ABM is valid or not.
based on said correlation value and its statistical significance, and 2) make interpretations about the SFP by analysing the conditions of those simulations that result in higher correlation values.

The foregoing, however, assumes that the point clouds obtained from the simulations will have a sufficient level of detail to be able to compare them with the photogrammetric record. However, if for any reason it is not possible to compare the distributions of wreck elements at the “microscopic” level of detail of the point clouds, then it should be done at the “macroscopic” level, from the analysis of objects and their relative positions.

3.4.3 Loss of structural elements due to shipwreck

This indicator allows exploring how much of the ship’s structure was lost during the shipwreck. It reports the difference between the number of structural elements of the ship, both major and minor, at the beginning of the simulation and at the end of the first month.

The pseudocode for this reporting process is:

- report (sum of major structural elements at the end of month 1 of simulation / sum of initial major structural elements) × 100

- report (sum of minor structural elements at the end of month 1 of simulation / sum of initial minor structural elements) × 100

Figure 14. Photogrammetric model of the USS Somers shipwreck generated by PAMGI during the 2018 field season. Above: a model of the complete wreck. Below: a detail of the bow area. From Ref. 7 Reproduced with permission from Aspha Ediciones. Both models by Rodrigo Pacheco y Felix Pedrotti.
3.4.4 Number of salvage operations
In terms of the historical explanation of the SFP, another necessary indicator is the number of salvage operations carried out on the shipwreck, both contemporary (systematic) and after the sinking (opportunistic). To the user interface and the text file of the simulation results we added an indicator of the total number of salvage operations. As mentioned in To salvage section, this number is stored during the configuration step in a global variable called total-salvages, which is the result of adding the values of the four types of salvages. Additionally, for systematic salvage operations, a similar indicator is used which limits the results to the period of the Mexican-American War (December 1846–February 1848).

The pseudocode for this reporting process is:

- report total-salvages
- report salvage count if current-year = 1847 or 1848

3.4.5 Wreck coverage rate
This indicator allows exploring how quickly the shipwreck would be covered by sediment deposition. It can be used to test, for example, various sea current conditions or sediment concentrations. For this indicator, we programmed a reporting process in which, at the beginning of each year, the area of the wreck that is above the maximum height covered by the sediment deposits is calculated.

The pseudocode is:

- if current-month = January
  - calculate wreck’s original-height = \( Z_{\text{max,original}} - Z_{\text{min,original}} \)
  - obtain maximum sediment height \( (Z_{\text{sediments}}) \)
  - calculate wreck’s current-height = \( Z_{\text{max,current}} - Z_{\text{sediments}} \)
  - calculate covered wreck percentage = \( \frac{(1 - (\text{current-height} / \text{original-height})) \times 100}{\text{final structural element count} / \text{initial structural element count}} \times 100 \)

3.4.6 Loss of mobile elements due to opportunistic salvage
This indicator allows the exploration of how much of the mobile elements located on the wreck’s surface was lost as a result of opportunistic salvage operations (i.e., those after the end of the Mexican-American War). Therefore, the process that generates the indicator only considers events after February 1848.

This indicator is linked to the Salvage process so that, if the latter is successful and the current-month variable corresponds to an opportunistic salvage moment, a report is generated with the name of the lost element and the corresponding month.

The pseudocode is:

- if (simulated-date \( \geq \) February 1848)
  - if (disappearance-success = true) AND (current-month = salvage-moment), report “missing item name, current-month”

3.4.7 Loss of structural elements due to degradation
This indicator allows the exploration of how much of the ship’s structure has been lost as a result of wood degradation. It reports the percentage of structural elements, both major and minor, lost at the end of the simulation.

The pseudocode for this process is:

- at simulation end
  - report (final structural element count / initial structural element count) \times 100
3.5 Degradation and deposition sequences

From our point of view, the central objective of studying archaeological sites from the perspective of SFP is to be able to answer, in as much detail as possible, the question: what happened here? That is, we seek to tell a story. Since telling a story necessarily implies the passage of time, it is essential that we can sequentially locate the events, whether natural or social, identified in the SFP. Obviously, the more detailed the chronological sequence, the more detailed the story we could tell.

Obtaining coherent chronological sequences of natural and social events is the goal of archaeological stratigraphy. However, since the stratigraphic analysis of a site is naturally linked to its stratigraphic excavation, establishing such a sequence will be almost impossible if the site is not to be excavated. In the best of cases, we would only be able to tell part of the site’s history, that of the systemic context, if the historical sources allow it. However, we would hardly be able to tell the second part of the story, that of the archaeological context.

This is where SFP simulation acquires great relevance as an interpretive tool since it allows us to recreate historical events to a certain extent. Furthermore, by using computational platforms to carry out the simulations, it is possible to obtain a chronological record of absolutely all the actors, variables, and processes, with the required detail, even in real-time. For this reason, in the Somers ABM, we considered it essential to include a chronological record of two types of events: 1) degradation and 2) deposition of ship’s elements.

A classical stratigraphic analysis would focus primarily on the sequence of element deposition.68 However, this assumes that the objects will degrade slowly enough that the archaeologist can observe them years or centuries after their deposition. This could be true for some submerged contexts whose environmental conditions are suitable for the conservation of archaeological materials, particularly wood (e.g., cold, deep water, with silt/clay sediments and anoxic environments). However, this is not usually the case in contexts located in tropical reef waters, such as the Somers, where environmental conditions favour wood degradation. In these contexts, an element may completely degrade in situ without ever being deposited on an interface (surface); such would be the case, for example, of the upper segments of the frames or hull planking. It may also be the case that objects fall and are deposited in the sediment but completely degrade after their deposition. In both cases, it would be very unlikely that archaeologists would find remains of such elements for them to be included in the stratigraphic sequence.

Therefore, in the ABM we included a record of both degradation and deposition. The model records each time a wooden element reaches 100% degradation and each time an element, be it wood or metal, makes contact with a sediment surface. In both cases, the moment (in milliseconds of simulation) in which the event occurred and the months that have elapsed are recorded.

The pseudocode for these processes is:

In Configuration:

- create “Degradation” and “Deposition” lists

On every Execution:

- for each wooden element
  - if degradation-percentage = 100, add to “Degradation”: element name + time (msec)

- for all elements
  - if it hits sediment bottom, add to “Deposition”: element name + seabottom name + moment (msec)

3.6 User interface

Here we detail the components contained in the ABM’s user interface, although we have already referred to most of them in other sections. The user interface is made up of three elements: 1) setup controls, 2) process monitors, and 3) simulation results.
3.6.1 Setup controls

The different controls described here correspond to the various sub-processes considered in Gibbs’ model, constituting variables whose values are used in different processes. Since their values alter both the way in which the ship’s 3D model is presented and the ABM’s processes, these controls should be defined by the user before starting the simulation (Configuration process).

In terms of CAS, defining these controls establishes the system’s initial conditions, while their different permutations allow evaluating different properties of the SFP as a complex system, including possible tipping points and emergent properties. In this case, different configurations of the element distribution in the shipwreck.

Although the definition of these controls can be completely arbitrary, ideally it should be based on historical data about the ship and its sinking process. Such was the objective of consulting historical sources about the Somers, presented in Historical sources on which the ABM is based section. Defining the initial conditions of the process in this way adds the dimension of human decisions to the SFP; that is, not only considering how the process happened but also why it happened that way.

We based these setup controls on Gibbs’ model, as detailed below.

- **Pre-impact — threat phase.**

  This sub-process refers to actions carried out, in the short and long-term, to avoid a naval accident. Long-term actions normally take place long before sailing, including the design of the ship itself, structural modifications, equipment, route, and even crew selection. Short-term actions are those taken during navigation when a threat may be perceived even though an imminent danger is not yet present.\(^{13}\)

  In the specific case of the Somers, the clearest long-term action was the metallic sheathing of the hull which, although not included in the ship’s plans, is present in the wreck. As for short-term actions, several are mentioned in Lt. Semmes’ and surgeon Wright’s accounts of the shipwreck, particularly after noticing signs of an approaching norther (i.e., strong wind or storm coming from the north), including increased alertness of captain and crew, manoeuvres to move away from the reef, and attempts to return to the anchorage site.\(^{28,29}\)

  However, although these actions add a certain historical aspects to the explanation of the SFP, most of them cannot be included in an ABM. It would be necessary to resort to other simulations to test the effect of these actions on the sinking process. The only action that it is possible to include in the ABM is the metal sheathing that covers the bottom of the hull and rudder blade, which is included in the 3D model and loaded into the ABM as a metallic agent.

Considering the above, the user interface does not include controls associated with this part of Gibbs’ model.

- **Pre-impact warning phase**
  
  o Were anchors dropped?
    
    ■ Controller options:
      
      • yes → anchors are removed from the 3D model
      
      • no (default) → anchors stay in place in the 3D model

- **Impact — crisis salvage phase**
  
  o The use of anchors can also be considered at this stage. However, since it was added in the previous one, it is not included again here.

  o Were heavy objects jettisoned?
    
    ■ Controller options:
• no (default) → all elements of the 3D model stay
• some → 0-50% (random) of carronades and cargo disappears
• all → all carronades and cargo disappear

○ Were masts cut? How many?
  ■ Controller options:
    • 0 (default) → masts remain unchanged
    • 1 → on either mast, middle and top parts are removed
    • 2 → on both masts, middle and top parts are removed

○ Were holes made on the hull?
  ■ Controller options:
    • no (default) → 3D model remains the same
    • yes, repaired → 3D model remains the same
    • yes, without repair → a random number of holes, between 1 and 10, are created in the hull (removing components from the outer and inner planking)

○ Were boats dropped?
  ■ Controller options:
    • yes (default) → boat disappears from the 3D model
    • no → 3D model remains the same

○ Were materials removed for survival?
  ■ Controller options:
    • no (default) → 3D model remains the same
    • yes, accessories → a random number < 20% of total accessory items (element-category = 2) disappear
    • yes, minor structural elements → a random number < 20% of total minor structural elements (element-category = 3) disappear
    • yes, major structural elements → a random number < 20% of total major structural elements (element-category = 4) disappear

○ Number of crisis salvage operations
  ■ Range 0 (default) to 10 (integers)

• Recoil — survivor salvage phase
  ○ Number of survivor salvage operations
    ■ Range 0 (default) to 10 (integers)
• Rescue/post-disaster phase
  o Number of systematic salvage operations
    ■ Range 0 (default) to 10 (integers)
  o Number of opportunistic salvage operations
    ■ Range 0 (default) to 10 (integers)

An important variable to consider in the analysis of the shipwreck SFP is the list of the ship, that is, if at the time of the shipwreck it leaned towards one of its rails and how pronounced this leaning was. This variable is not contemplated in Gibbs’ model but would affect the distribution of observable elements in the shipwreck.

The accounts of the *Somers*’ wreck mention it listed to starboard and thus went to the bottom. Since we don’t know precisely how many degrees it heeled over, we added two controls to the simulation’s configuration:

• Did the ship list?
  o Controller options:
    ■ no
    ■ yes, to port
    ■ yes, to starboard (default)

• Degrees of list
  o Range 0 to 90°. Note: we determined this range considering the specific case of the *Somers*. However, since it is possible that a ship’s hull may turn 180° during a shipwreck, this range should be extended to 360° in future versions of the ABM to give more freedom to this parameter.

Finally, we added End simulation month and End simulation year selectors to allow the user to enter a specific date for ending the simulation and explore what the conditions of the shipwreck and the different indicators would have been on that date. The default options are defined as “August” and “2018”, the date on which the photogrammetric record of *Somers* was carried out by PAMGI.59

### 3.6.2 Monitors

The second component of the user interface is monitors, non-user-modifiable indicators that are visible at all times throughout the simulation, providing relevant information in real-time. Monitors include:

• Simulated date: shows which month and year the current moment of the simulation corresponds to.
• Elapsed months: the number of “months” that have passed since the start of the simulation.
• Salvages: shows the number of salvage operations programmed in the configuration, both total operations and each of the four types of salvage.
• Wood degradation percentage: the global degradation percentage of all remaining wood agents in the simulation.
• Metal corrosion percentage: the overall corrosion percentage of all remaining metal agents in the simulation.
• Number of remaining pieces: the total number of pieces left in the simulated shipwreck.
• Covered wreck percentage: the proportion of the remaining volume of the wreck that is covered by sediment agents.

• Simulation duration: the elapsed time, in minutes and seconds, since the simulation started.

3.6.3 Simulation results
The last element in the user interface is a dialogue box showing the results of the simulation, i.e., the indicators mentioned in the previous section. It includes:

• end date of the simulation

• percentage of structural elements lost, both total and due to shipwreck

• number of salvage operations (total and of each type)

• number of mobile elements lost due to shipwreck

• number of pieces remaining

Additionally, the dialogue box provides the user with an option to export the simulation results. If chosen, the process of creating text files for both results and point cloud and exporting them to a user-defined location is executed.

3.7 Initial conditions for SFP simulation
To explore the Somers shipwreck SFP and test different historical hypotheses, the ABM should start from a set of initial conditions, resulting in quantifiable differences in the different indicators, particularly the distribution of elements in the wreck. Such conditions are based on historical data of the wreck, so for those where historical records are available, conditions remain constant. Meanwhile those for which there is no historical evidence are variables that can be explored in the simulation. Thus, for example, the accounts of the wreck of the Somers do not mention that the anchors were dropped but they do mention that the boat was launched; there is also no mention of crisis or systematic salvage operations. These data should remain constant in all simulation scenarios. On the contrary, since there are no records on opportunistic salvage operations, this remains a variable from which different scenarios can be simulated.

Based on our review of historical documents related to the Somers wreck (Historical sources on which the ABM is based section), the initial conditions that should remain constant for its SFP simulation are:

• anchors were not dropped

• heavy objects were not intentionally jettisoned

• masts were not cut

• no holes were made in the hull (since the ship did not crash)

• the boat was launched

• there was no intentional removal of survival materials

• there were no crisis salvage operations

• there were no survivor salvage operations

• there were no systematic salvage operations

4. Discussion
In 2008, Mexican maritime archaeologist Jorge M. Herrera wrote in his doctoral thesis about the possibility of experimentation in archaeology: “Maritime archaeology is sadly limited in its options in regards to experimentation, as it would be rather impractical to go [...] and wreck several boats to see if the conceptual models matched reality”.

This statement is directly related to the nature of archaeologists’ object of study since we face the challenge of trying to narrate an entire film by seeing only the last scene. We put together conceptual models, hypotheses, and interpretations about what could have happened during the film in order to end up with this scene. But the scene we see, the archaeological context, is not a fossil frozen in time but the result of interactions between many factors over many years. Furthermore, as the magnitude and type of such interactions have surely changed over the years, the site formation process is not linear, which leaves us with a wide range of possible interpretations of stories to tell. How, then, can we distinguish among the range of possible stories which one(s) are most likely to have occurred and be best suited to telling the site’s story? The task of discerning the SFP is even more complicated when we consider that archaeologists are working with an “unrepeatable experiment”, especially when it comes to excavation. That is, we cannot repeat history to prove what could have happened and what could not. It is not practical, as Herrera said, to sink several boats to see which conceptual model most closely resembles reality. We can't rebuild the USS Somers and sink it again … can we?

Today, we are less limited in our capacity for experimentation in maritime archaeology. Through the use of computational tools such as ABM, we can make the experiment repeatable. We can test different conceptual models of the SFP, simulate different scenarios with different process conditions, and see in what archaeological context they result. We can put together and dismantle the Somers as many times as we want. Such is our proposal: that from the standpoint of CAS, an ABM could serve as a tool for postulating a sustained interpretation of a shipwreck’s SFP.

A particular characteristic of the archaeological study of SFP is that they leave little room for easy or even fantastic interpretations of historical events. When we are not very clear about the story or when it has several gaps, SFP force us to base our interpretations on data and make our assumptions explicit. This is where, to our view, ABM can be a fundamental tool for archaeologists interested in SFP. Not only does ABM allow us to make the experiment repeatable, it requires us to make our assumptions explicit by defining variables, processes, indicators, scenarios, and hypotheses in a conceptual model. In this paper, we presented such a conceptual model about the SFP of Somers, which is not intended to be definitive in any way, but rather the first implementation of a tool that allows testing hypotheses in order to tell a story more or less reliable, with firm supports, about the Somers shipwreck.

As stated earlier, we based our ABM on the theoretical models of maritime archaeologists Keith Muckelroy and Martin Gibbs. In his seminal article on the cultural aspects of shipwreck SFP, Gibbs referred to further developments on various aspects of Muckelroy’s model stating that:

“For both Souza’s (1988) and O’Shea’s (2002) studies make significant advances in our understanding of cultural ‘scramblers’ and ‘extracting filters’, it could be argued that the ‘pre-depositional’, ‘depositional’, ‘post-depositional’ structure is still primarily oriented towards explanation of the archaeological deposition and distribution, rather than the cultural processes behind them. [...] I would suggest that the alternative way of approaching shipwrecks as cultural processes is to structure our understanding around the nature of the event and the sequence and range of potential responses at each stage.”

In our opinion, the fact that Gibbs considers Muckelroy’s approach and the subsequent developments by Souza and O’Shea as limited in their ability to explain cultural processes is because he may be asking for the impossible. That is, he is hoping that Muckelroy’s model will provide a historical/social explanation of a shipwreck SFP when it is not necessarily trying to do so. The same argument could be used in the opposite direction. It could be said that Gibbs’ model does not explain the deposition, degradation, and distribution of elements of a shipwreck; but it does not do so because that is not its objective. Rather, it seems that the Muckelroy and Gibbs models bring two different levels of explanation to understanding the shipwreck SFP: one the time’s cycle, the other the time’s arrow.

The time’s cycle and arrow metaphors come from Stephen Jay Gould’s homonym book (Time’s Arrow, Time’s Cycle, 1987). This text is cited by Edward Harris in his Principles of Archaeological Stratigraphy (1989) to illustrate two aspects of the study of stratification in an archaeological site: the cyclical and the historical aspects. The archaeological stratification of a site, with its stratification units (deposits and interfaces), represents the time’s cycle insofar as its formation is always the result of “the same, repetitive processes, i.e. deposition or degradation”. Consequently, they are timeless and universal, being found in any archaeological site in the world. The interpretation of the structure of the site and its artefactual content provide the time’s arrow, the historical aspect of the stratification. “Without an appreciation of the difference between the two bodies of data that represent time’s arrow and time’s cycle, the unique event from the repetitive process, it will be difficult for an archaeologist to understand, record and interpret archaeological stratification”.

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From this distinction between time’s cycle and time’s arrow, the apparent discrepancy between Muckelroy and Gibbs’ models could simply be that they each address different aspects of the SFP. In our opinion, Muckelroy’s model and its subsequent extensions are more oriented towards the cyclical, timeless aspects of the process including environmental factors, extracting filters, and scrambling devices, as well as the effects they produce, which we will find in all shipwrecks, places and times. Gibbs’ model addresses primarily the historical, temporal aspects of the SFP such as the motivations and decisions of different people in different places and at different times. In this sense, both models do not seem opposite but totally complementary. One provides the how of the story, the other the why. Hence, the ABM we developed integrates components of both theoretical models.

A fundamental principle when creating an ABM is to start simple, with the fewest possible number of elements (agents, variables, processes) that would allow us to answer our research questions. Since we based our ABM on the theoretical models of Muckelroy and Gibbs, whose general characteristics were conceived to be applicable to any shipwreck, it contains the fewest possible agents, processes, and indicators to explore their SFP, and should be suitable for other shipwrecks without major modifications. However, in its current version, our model is specific to the Somers and was designed to explore specific questions about this particular shipwreck based on its story. Therefore, for our ABM to be used in other case studies, some extensions to the conceptual model would be necessary.

Regarding the model’s processes that simulate environmental aspects of a shipwreck SFP, they should be extended to consider the hydrodynamic effects of high or low energy conditions, which differentially modify the shipwreck through physical or chemical-biological erosion processes. Some of these effects are considered, for example, in the fluid dynamics simulations carried out by maritime geophysicist Rory Quinn.

However, the central role assigned to fluid dynamics in Quinn’s studies of shipwreck SFP is based on “the acceptance that physical processes dominate early-stage wreck site formation”. This “acceptance” may be rather obvious from his perspective as a geophysicist, given that the interactions of the shipwreck-current-sediment start when the ship is deposited on the seabed, which may seem to be where the process begins. But it is not so clear from an archaeological point of view, which considers that the SFP begins long before the deposition of the ship and that it not only involves physical processes but also a series of decisions by various agents at different moments of the process, such as those considered by Souza and Gibbs, which modify the configuration of the shipwreck in its entirety. From this perspective, it is apparent that physical processes constitute one of many components of the SFP, not necessarily the dominant one.

Regarding the wrecking process, two necessary extensions for the ABM would be needed to simulate 1) catastrophic wrecking, and 2) the sinking process. The first extension would allow simulating different wrecking scenarios, such as grounding and battle, where the ship would have undergone serious structural damage. We did not define such processes in our conceptual model since none of these happened to the Somers, which sank after capsising due to weather conditions. Because of this, even though the setup controls allow for the selection of initial conditions that would modify the ship’s configuration (jettisoning, cutting masts, holes on the hull), simulations for the Somers’ SFP would start with the ship rather intact, settled on the seabed.

However, even in the absence of major structural damage, the sinking process itself can potentially alter elements’ disposition within the ship and, consequently, the seabed distribution of the shipwreck, due to spatial rearrangements during the transit from surface to bottom. This would be especially true for ships sinking in deep waters, such as the Somers. Therefore, the ABM should be extended to simulate the sinking process. This would allow for the exploration of the effect of variables such as cargo and ballast distribution, nautical manoeuvres, list, and position of the ship when deposited on the seabed. Such an extension could also be designed to allow for simulating wrecking scenarios with different depths to explore, not only the aforementioned effects of the sinking process, but also if shallower depths would increase the probability of pieces disappearing during salvage operations.

The Salvage process could also be refined in future versions of the ABM. In its current configuration, all salvage operations are equivalent in terms of the number and type of objects that can be removed from the environment as a result of each operation. This is because the probability of object disappearance is a function of the value assigned to them, which we assigned arbitrarily and remains constant throughout the simulation time. This value assignment is probably inaccurate in historical terms, but we assumed it that way in order to simplify the ABM. In future versions of the model, value assignment could be refined so that it is not fixed from the start, but rather reflects the different interests of different actors at different times, along the SFP. For example, a sailor would probably not have been interested in salvaging an artillery piece from the wreck in the event of a survivor salvage operation. Therefore, the piece’s value during said operation would be very low. But the opposite could be true if it were the Commodore who planned a systematic salvage operation, then artillery could be most valuable to the rescue.
Additionally, the Salvage subprocess is executed only on those elements categorised as mobiles and accessories. The four element categories (major structural, minor structural, fixtures, and cargo) were taken directly from Gibbs, who proposed them as a way to “simplify and characterise the components [...] based on the relative ease with which items can be removed and how they relate to the structural integrity of the vessel”. However, he also pointed out that this categorisation of elements is “flexible and not strictly hierarchical”. For example, a component of the cargo located in the bottom of the ship would be assigned category 1 (cargo) but could be much heavier or more difficult to access than a fixture (category 2) or structural element (categories 3 and 4) located elsewhere in the ship. From our point of view, the possible conceptual limitation of element categorisation that Gibbs observes is completely avoided in our ABM by being based on a 3D environment and programmed so that processes involving element removal are not based merely on item category but rather on a salvage difficulty calculation, which involves both the item’s mass (in turn affected by degradation) and its three-dimensional location.

In addition to salvage operations, the model should also be extended to include other intrusive operations. We refer in particular to archaeological operations, particularly excavation, which constitute an important part of a shipwreck SFP as they profoundly modify the shipwreck’s element content and spatial disposition. As with other conditions, we did not include such operations in the current version of our ABM, since no intrusive archaeological operations have been carried out so far in the Somers shipwreck.

Finally, using ABM would potentially allow archaeologists to explore how much of a shipwreck’s SFP can we know if we were only to perform a surface, non-intrusive recording, that is, without excavating the shipwreck. With this in mind, we added to the ABM an additional component that is obviously not found in any of the theoretical models: the degradation and deposition sequences. Traditionally, these could only be obtained from the archaeological records of a stratigraphic excavation; however, with ABM this is no longer a limitation. By integrating the analysis of such sequences into the analysis of the SFP we could refine our understanding of its cyclical parts, thus refining our timeline and the story we tell.

5. Conclusions
In this paper we have tried to provide a glimpse of the scope ABM could achieve as a tool for the archaeological study of site formation processes, specifically shipwrecks. Although this type of modelling, has been increasingly used in archaeology as a methodology for analysing complex systems, to our knowledge, this is the first time it has been applied for studying SFP.

Through ABM it was possible to integrate two different but complementary theoretical models, and several sources of information as diverse as 19th-century shipbuilding plans and specifications, eyewitness accounts, and official naval reports from the time; but also contemporary oceanographic, geophysical, and archaeological data. All of these were coherently and interrelatedly integrated into a model designed for analysis and experimentation.

The fundamental contribution that our modelling proposal gives to the archaeological discipline, in general, is the possibility of proposing a wide variety of hypotheses and carrying out controlled and repeatable experiments that were not possible before. This directly impacts our ability to analyse and interpret the archaeological context and, thus, the ultimate goal of the discipline, which is to answer questions about the past. In the field of maritime archaeology, in particular, our proposal contributes to providing the discipline with a methodological tool that, through the integration of conceptual models, historical sources, and archaeological data, allows for generating sustained interpretations of shipwrecks and their site formation process.

Author contributions
RVS: Conceptualisation, Data Curation, Formal Analysis, Investigation, Methodology, Software, Supervision, Validation, Visualisation, Writing – Original Draft Preparation, Writing – Review & Editing.

JMH: Data Curation, Formal analysis, Funding Acquisition, Investigation, Methodology, Project Administration, Resources, Writing – Review & Editing.

Data availability
Extended data
Vega-Sánchez R. Supplementary material for “Agent-based modelling for the study of shipwreck site formation processes: A theoretical framework and conceptual model”. OSF; 2022, DOI 10.17605/OSF.IO/2H97R. Available from: https://osf.io/2h97r/70
This project contains the following extended data:

- Supplementary material 1. Degradation and corrosion equations.
- Supplementary material 2. Coral adherence/growth.
- Supplementary material 3. An alternative for coding the movement process of mobile agents.

Extended data are available under the terms of the Creative Commons Attribution 4.0 International (CCBY 4.0).

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General statement about the manuscript:

The article is well-written and organised and provides an insightful archaeometric approach to shipwrecks interpretation, with an emphasis on the application of a novel and useful tool for better understanding the site formation process (SFP).

I think this proposal is very exciting. To conceive shipwreck SFP as complex adaptive systems (CAS) provide scholars with a powerful heuristic tool (in this case, agent-based modelling – ABM) to obtain non-linear and multi-causal answers about complex behaviours comprising both human and natural factors and dynamics. Furthermore, considering the observable elements of a site as an emergent phenomenon that result from the interactions and changes developed over time between different agents, and addressing how the behaviour of agents led to a particular result (a pattern in the archaeological record) are both original approaches that could be applied to the analysis of SFP of other shipwrecks. With a high degree of novelty in the field of nautical archaeology, this study applies a methodological approach of computational modelling and simulation (ABM tool) to attain shipwreck SFP, which is very valuable considering the inner limitations that the documentary and archaeological information usually present about a particular ship’s life and environmental and cultural conditions that surrounded it through time.

The methodological procedure to develop the ABM code is well-developed. Also, the information used to feed this model is clearly presented and detailed. For instance, the nautical features of the USS Somers, needed to define the 3D model of the ship, were defined based on previous solid research on documentary evidence, an archaeological non-intrusive record of the site, and proxy data from other contemporary US naval vessels. The different elements that comprise the conceptual model used by the authors, their main characteristics and structure, are also
explained. Nonetheless, I suggest minor amendments in some individual attributes or properties of a few agents to improve their reliability (see below).

The sections “3. Process” and “4. Indicators” are well-explained and justified (I went through the statistical features of pseudocode for different operations, from 3.3.2.1 to 3.3.2.5), yet minor changes are also suggested (see below). The section “5. Degradation”, I think it could be merged into a previous section. The section “6. User interface” is clear, yet an image on the interface controls would be helpful to better understand it.

As it is stated in the discussion, this research developed and applied a powerful heuristic tool to test different situations under different and variable conditions to assess the SFP of the USS Somers and provide a series of possible histories to be then tested against the archaeological record, thus contributing to both the time's arrow and time's cycle and gaining a deeper and more reliable understanding on the actual natural and cultural processes to which it was subjected through time.

The manuscript is accepted for indexing after minor revisions on the aspects detailed below are developed.

Please, consider replacing the following expressions or terms:

- Section 2.2.1: metal lining covering the bottom for metal (or copper) sheathing.
- Section 2.2.1: rudder blade for rudder (also, see its mention in other sections of the manuscript).
- Section 2.2.1: water lines for waterline.
- Section 2.2.1: ¿what do covers stand for? ¿do you mean decks or deck planks?
- Section 2.2.1: tubular metal stock for metal stock or movable iron stock.
- Section 2.2.2: the hold located on the bottom of the hull for the hold (the clarification is unnecessary)
- Section 3.1.2: stern foot for stem foot.
- Section 3.1.2: bullets for shot.

Please, revise the following expression:

- Section 2.2.1: stanchions that supported both covers, knees, beams that supported the lower deck...

Please, revise the following statements:

- Section 2.2.1: “Anchors were probably of the “Old Pattern Admiralty Long Shank” type, adopted by the British navy at the end of the 18th century and in use for much of the 19th century”. The information on the use of this type of anchor is incorrect. By the time UN Navy built and equipped the USS Somers, it is most likely that one of the new models patented since the 1820s was used for that purpose. Please, revise a more specialized and precise bibliography on this theme (see Curryer, 1999; Ciarlo, 2019, 2023, and references therein). To consider this and other technical comments would be significant for authors to better
define the individual properties of agents that make up the ABM.

- Section 2.2.1: “wrought iron density = 484 pounds/ft³”. The density of cast iron should be considered for pig iron ballast, which was made of this material. It ranges from about 6.9 to 7.4 g/cm³ (among cast iron, white iron in particular has the higher value of density).

- Section 2.2.1: “distributed along the centre of the hold”. Pig iron (small ingots) was also distributed aft and fore the ship’s central area (see Carabias et al., 2023).

- Section 3.1.1: “our ABM starts with the ship already settled on the seabed, that is, the model does not take into account the transit from the water surface to the bottom. Although this transit could certainly have altered the distribution of elements of the ship, in this first version of the model we assume that such alteration was minimal”. This can be applied with a degree of confidence in this case; although, other wreck events (e.g. in a blast or fire) comprise a high disturbance of the structure, equipment, and other elements between the two stages. Depth and drift of the remains during sinking should also be considered here.

- Section 3.1.2: “…for the ABM we considered that wood is already saturated at the beginning of the simulation”. It probably took a while for a ship’s timber to be fully saturated with water. Considering the dynamic potential of the ABM proposed by authors, I think this change over time should also be considered in order to apply the model.

- Section 3.1.2: “The nails used to fasten the linings were usually made of copper, zinc, or tin alloy”. As a general statement, one can pose that at that time wooden vessels sheathed with copper (or brass sheets) were fastened with copper or copper-based fastenings (e.g. bronze bolts and bronze nails) below the waterline. Above it, most fastening and other metal fittings were made of iron, given the former was more expensive. This scheme seems appropriate to the case of USS Somers (see McCarthy, 2005; Ciarlo, 2017, 2023; and references therein).

- Section 3.1.2: “Creuze's mention that the nails were not made of pure copper but of an alloy of zinc, copper, and tin may suggest the use of naval brass. Therefore, for ABM we assumed that the latter was used for the hull sheathing”. This assumption is not correct. Bolts and other fastenings were indeed made of naval brass, but sheathing planks were made either of unalloyed (pure) copper or brass (the latter, with no addition of tin, as they were manufactured by rolling) (see the suggested bibliography).

- Section 3.1.2: “…chains, anchors, and carronades are cast iron”. Despite guns, both chains and anchors were manufactured with wrought iron.

- Section 3.1.2: “Hull sheathing is naval brass”. This should also be changed for the analysis. We actually know that the sheathing of the USS Somers was made of pure copper (as well as the sheathing of other US naval vessels of the time such as the USS Constitution).

- Section 3.1.2: “The salvage-value attribute is a continuous numerical variable whose initial values were assigned to each agent arbitrarily. We assumed that, similar to the previous example, artillery, ammunition, or some equipment would be more valuable for salvaging than structural elements”. I think it rather depends on the situation of the wreck and the
survivors’ necessities. If they were compelled to build a camp or another vessel to sail away and survive, timbers would have been most valuable for them.

- Section 3.1.2: “The degradation-percentage attribute is a continuous variable”. It would be interesting to add a correction value depending on the environmental conditions where the wreck site is located, or at least to mention the possible variations that can be expected if different water conditions are faced.

- Section 3.3.2.3: “…models of shipwreck SFP should include at least some rigging elements. However, we decided not to include these elements nor their degradation process in the Somers”. The two reasons why authors decided not to include rigging (lack of precision in documentary sources and lack of experimental data) seem not sufficient given these drawbacks did not hinder them to include in the model other ship’s elements for which they had not this information either. The authors mentioned that experimental data for wood and metal is available, but this information is of a general nature. Differences between ferrous and non-ferrous alloys are considered (iron versus brass), but no distinction is established within ferrous alloys, e.g. differences between wrought and cast (and within the cast iron, between grey and white). For the sake of analysis, is it not possible to include rope within the wood category (or a general one, for organic materials)?

- Section 3.4.4. “In terms of the historical explanation of the SFP, another necessary indicator is the number of salvage operations carried out on the shipwreck, both contemporary (systematic) and after the sinking (opportunistic)”. As no documentary data are available about the first three types of salvage operations defined by Gibbs, how is it possible to establish a reliable criterion for these activities after the sinking?

- Section 3.7. “the accounts of the wreck of the Somers do not mention that the anchors were dropped but they do mention that the boat was launched; there is also no mention of crisis or systematic salvage operations. These data should remain constant in all simulation scenarios”. That a certain action is not mentioned in the documentary sources does not mean that it actually did not take place in the past. At least in the case of actions that likely occurred during a sinking event such as the one experienced by the USS Somers, I think they should also be tested (as well as activities for which no records are available).

I suggest considering the following works:

- On the background on SFP of shipwrecks:
  - Fernández-Montblanc et al. (2016)
  - Fernández-Montblanc et al. (2018a)
  - Fernández-Montblanc et al., (2018b)
  - Ortega Pérez et al. (2023)
- On anchors (particularly, the Old Admiralty Long Shank Pattern and other types used during the 19th century):
  - Ciarlo (2019)
  - Ciarlo (2023)
  - Curryer (1999)
- On pig iron, a recent historical and archaeological detailed account of its use in mid-19th century ships is provided by:
  - Carabias et al. (2023)
- On metal fittings and fastenings of late 18th to mid-19th century wooden vessels with
copper sheathing, see:
Ciarlo (2017)
Ciarlo (2023)
McCarthy (2005)

References

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and is the work technically sound?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Yes

If applicable, is the statistical analysis and its interpretation appropriate?
I cannot comment. A qualified statistician is required.

Are all the source data underlying the results available to ensure full reproducibility?
Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Maritime and nautical archaeology, historical metallurgy, and archaeometry

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 23 March 2023

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The article proposes a new approach for studying the shipwreck site formation process (SFP) in maritime archaeology, using a complex adaptive system (CAS) approach and agent-based modelling (ABM). The authors argue that while previous SFP models based on systemic theory have been valuable, they fall short in explaining the distribution of elements in a shipwreck. By applying the principles of CAS and ABM, the authors suggest that it is possible to better understand the interactions between various social and natural elements in the formation of an archaeological site, using the 19th-century USS Somers as a case study. A detailed overview is then provided about the different components of an ABM that could be applied to address the authors' research questions.

Overall, the article and methods are well thought out and provide a novel approach to addressing the challenges of studying SFP. The different processes and components of the model are well-described and easily understood. This will be an incredibly useful paper on how to conceptualize a model for future implementation, especially on a topic that has yet to receive any ABM attention. However, to improve the readability and overall flow of the paper, I recommend the following structural changes and additions, detailed by subheading.

Section 3 Results: this section would be more appropriately termed Theoretical Model Description since the authors are not presenting results of the actual outcomes of the model. I would also recommend that a brief paragraph description be given of the model and what it will do prior to outlining the specific components beginning in section 3.1. I would also recommend
revising the overall model subsections to follow the ODD protocol (Grimm et al. 2010. The ODD protocol: a review and first update. *Ecological Modelling* 221: 2760-2768). Adaptation of an ODD will also make it easier to follow the logic of the different model components discussed. For instance, Section 3.1.1 falls under the agents subheading, but it is unclear if this is being used as an overall model environment or if the environment is being used as an agent and how. I recommend that the authors re-think if all of the components are actually agents or model environment parameters and potentially add a specific sub-section on environment parameters which is currently missing from the model description. Adjustment to an ODD model description will make it easier for the reader more fully comprehend the proposed model design and would follow the standard approach for describing archaeological models.

**Section 3.3 Processes:** it is unclear why pseudocode is provided for some subprocesses and not others. Given the length of the paper, I question the necessity of including the pseudocode sections. I urge the authors to consider including the full pseudocode within supplementary material and only mention the relevant processes. This would also allow for a better understanding of how the model will be run without having to refer to individual sections within the article.

**Section 3.4 indicators and their analysis:** a general overview of the different validation datasets and techniques should be included prior to going into detail in the subsections. 3.4.2 goes into detail about how the simulated dataset will be validated against real-world data, however, the other subsections do not. Alternatively, a discussion of the model's validation could be better suited to be expanded upon in the discussion section, see below.

**Discussion section:** the first part of the discussion section would be better suited in the introduction (1.1.4) where the authors discuss ABM as a tool for addressing their research questions. Notable is the absence of a discussion on how the model will be critically validated and what methods of analysis will be used. I recommend that the authors also think about how changes to the model will need to be done if validation is inaccurate. The authors have provided a comprehensive discussion of the benefits of applying ABM to their research questions; however, this section would be improved by addressing the limitations of the approach, and discussing how these might be mitigated by other approaches or analyses. Additionally, the authors have also not stated if this model will actually be created or if the aim is to just present the theoretical model concept for potential implementation by other archaeologists.

Some other minor points:

- p.7 (of the pdf version of the article) further description of why ABM is more appropriate than other methods such as fluid dynamic models is needed. It's still not completely clear why ABM should be applied in this case study.

- Some of the figures need to be included at a higher resolution. Figure 8 needs to be amended so that the text is all readable; Figure 11 text is a bit blurry; Figure 13 is quite blurry, if possible, I recommend a higher resolution image.

- In the general description of the ABM on p. 14, additional commentary on how the static and dynamic agents were chosen as the most relevant for inclusion in the present model is needed.
References

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and is the work technically sound?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Partly

**Competing Interests:** No competing interests were disclosed.

**Reviewer Expertise:** Archaeology, simulation, computational archaeology

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.
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