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Modelling cultural evolution processes in Dressel 20 amphora production during the Roman Empire

María Coto-Sarmiento [a,b,c], Simon Carrignon [d,e,*]

[a] School of Culture and Society - Centre for Urban Network Evolutions (UrbNet), Aarhus University, Moesgård Allé 20, 4230, 224, 8270 Højbjerg, Denmark
[b] HUMANE, Human Ecology and Archaeology Research Group, Department of Archaeology and Anthropology, Milà i Fontanals Institution for Research and Humanities, IMF-CSIC, C. Egipciaques 15, 08001, Barcelona, Spain
[c] School of Culture and Society - Social Resilience Lab, Aarhus University, Jens Chr. Skous Vej 7,4. etage, 8000 Aarhus C, Denmark
[d] McDonald Institute for Archaeological Research, Downing Street Cambridge CB2 3ER, United Kingdom
[e] Department of Genetics, Evolution and Environment, University College London, Gower Street London CB2 WC1E, United Kingdom

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A B S T R A C T

How people interact socially and transmit their knowledge from generation to generation leads to different habits and traditions. When these traditions are about pottery-making techniques, these differences may have left a quantifiable trace in the remaining cultural material. However, linking the differences observed in the archaeological record with social learning strategies and how production techniques were transmitted is extremely difficult. In archaeology, this has been studied in handmade production but barely analysed in large-scale production implying long-distance social interaction during an extended period. The goal of this study is to explore the transmission of technical skills among potters within the Roman Empire. Specifically, our case study has focused on the Dressel 20 amphora production processes based in *Baetica* province (currently Andalusia). To achieve this, we (1) compute the covariance matrix between morphometric measurements and use it to define the core rules of pottery-making techniques, (2) define scenarios in an Agent-based model that represent hypotheses about how techniques were shared between potters, and (3) quantify how likely each scenario is to reproduce the correlation between morphometric similarity of the pottery and the distance between the workshops observed empirically.

Our analysis highlights that, while the spatial distribution of workshops influences social interaction among potters, it does not act as a strict barrier. Even workshops that are relatively distant can exhibit some morphometric similarities, suggesting that knowledge and techniques can be transmitted over larger distances. However, to obtain the level of correlation between distance in space and closeness in shape observed in the real world, geographical constraints – represented in our case by riverine connections – need to play a role in limiting interactions. Finally, we believe this method provides a versatile framework to explore morphometric differences related to the transmission processes in a large-scale production.

1. Introduction

The diverse social interaction and transmission of knowledge from generation to generation lead to different habits and traditions (Boyd and Richerson, 1988; Basalla, 1988; Eerkens and Lipo, 2007; Shennan, 2008). In the context of pottery production, these differences may have left quantifiable traces within the remaining cultural material (Neff, 1992). However, establishing a definitive correlation between the observed variations in archaeological records and the social learning strategies used in the transmission of production techniques becomes extremely challenging. While handmade pottery has been extensively studied (Neff, 1992; Neiman, 1995; Shennan and Wilkinson, 2001; Steele et al., 2010; Roux, 2013, 2015), these processes in the context of large-scale production, have been barely analysed, especially in long-distance social interactions (Aguilera, 1998; Berni, 2008; Coto-Sarmiento et al., 2018; Rubio-Campillo et al., 2018; Coto-Sarmiento and Carrignon, 2023).

This work presents a novel approach that addresses these concerns by applying an Agent-Based Model in combination with archaeological data and considering geographical distance. In particular, we used an Agent-Based Model to explore different cultural transmission processes in Dressel 20 olive oil amphora production from the 1st to the 3rd century AD during the Roman Empire. This study aims to test various

* Corresponding author.
E-mail address: s.carrignon@ucl.ac.uk (S. Carrignon).

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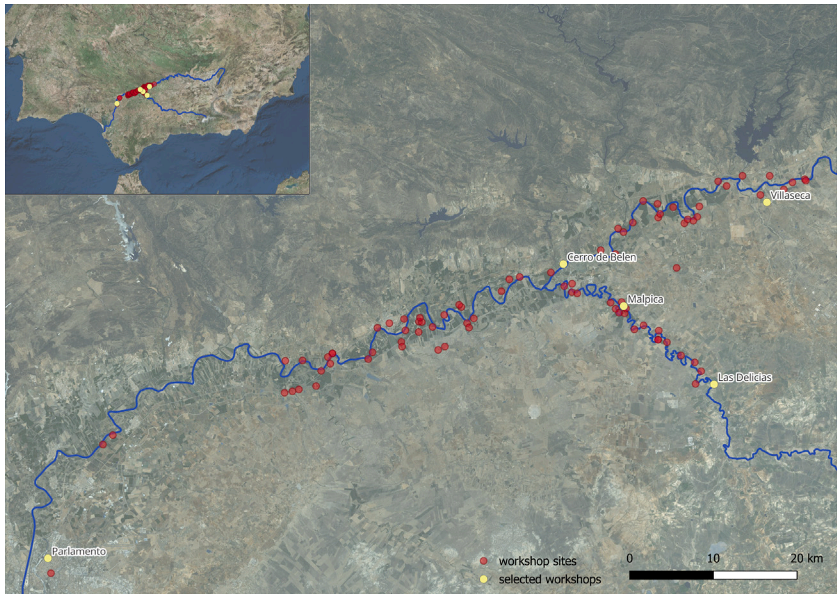

Fig. 1. Hundreds of amphora workshops concentrated in *Baetica* province during the Roman Empire. The location of the workshops (red dots) shows how Dressel 20 workshops were mostly distributed along the rivers Guadalquivir and its tributary Genil. Yellow dots, including the names, correspond to the 5 workshops selected for the analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

potential transmission scenarios to determine how pottery workers transmitted and spread their skill knowledge to others by studying the large-scale production of massive amphorae during the Roman Age. The model also integrates the importance of the Guadalquivir River and its Genil tributary for the transmission of knowledge and techniques in the amphora production (Chic, 1984; García Vargas, 2010; Berni and García Vargas, 2016).

2. Modelling the cultural change in *Baetica* province

Olive oil was an essential product in daily life in the Classical Mediterranean world (Remesal, 1977; Mattingly, 1988). The substantial demand for olive oil from the Empire promoted the creation of a vast infrastructure for amphora production located in the *Baetica* province (current Andalusia, southern Spain). The olive oil amphorae called Dressel 20 were shipped throughout the Empire and served as a crucial supplier for military campaigns and the city of Rome (Remesal, 1986; Carreras Monfort, 1998; Funari, 2005). Hundreds of specialised amphora workshops were located on the banks of the Guadalquivir River and its tributary Genil (Remesal, 1998) (see Fig. 1).

The location of the amphora production in a strategic area full of olive trees and close to the rivers allows large-scale transportation of olive oil production via the Mediterranean and Atlantic maritime trade routes connecting *Baetica* with the rest of the Empire (Remesal, 2002; García Vargas, 2010; Rubio-Campillo et al., 2018; De Soto, 2019). The importance of the Guadalquivir and Genil rivers extends beyond providing access to natural resources. Along with facilitating the olive oil trade throughout the Empire, the concentration of workshops along their banks was crucial for more frequent contact among workshops in the transmission of production techniques (García Vargas, 2010; Rubio-Campillo et al., 2018).

Roman olive oil production has been characterised by a large activity from the 1st to the 3rd century AD (Remesal, 1977, 1998; Berni, 1998; Chic, 2005). The importance of this long period of activity also suggests a highly specialised production with many qualified workers, learning specific and specialised skills over multiple generations.

This large-scale distribution is clearly illustrated by the massive number of Dressel 20 amphorae found throughout the Empire, particularly in western provinces (Dressel, 1879; Berni, 1998). This special type of amphora has been identified as the main amphoric vessel for the storage and transport of olive oil. Dressel 20 amphora is a well-known container for its particularly globular form, short neck, and oval and short handles. The form of this amphora and its massive production indicate a high degree of standardisation where the same type of amphora was made for almost three centuries (Berni, 1998, 2008).

However, despite the existence of many archaeological data on this well-known amphora production, challenges remain regarding (1) the organisation of amphora workers during the Roman Empire, (2) the impact of large-scale production on the diffusion of skill techniques between workshops and (3) how techniques spread between generations to maintain a highly standardised amphora type.

Here, we develop an Agent-Based Model to explore two hypotheses based on the results and data published in the paper (Coto-Sarmiento et al., 2018): (a) different social learning processes generate distinct patterns observable from amphora production and (b) the interaction between spatial distance and morphometric variation can be quantified and used to test the frequency of social interactions within a region.

In previous studies (Aguilera, 1998; Coto-Sarmiento et al., 2018), similarities in morphometric features in amphora Dressel 20 were found between the closest workshops. It is assumed that geography can make interactions harder or easier depending on the distance (Wright, 1943; Van Strien et al., 2015; Shennan et al., 2015). This process, often described as "isolation by distance", reflects the fact that nearby workshops tend to interact more than distant ones and are more likely to share similar amphora-making techniques and therefore produce more similar amphorae. In this work, the aim is to use an Agent-Based Model to explore what specific processes of cultural interaction can reproduce the similarities observed in previous studies (Aguilera, 1998; Berni, 2008; Berni and García Vargas, 2016; Coto-Sarmiento et al., 2018; Coto-Sarmiento and Carrignon, 2023).

The Agent-Based Model will simulate a theoretical process of knowledge exchange of technological skills between pottery workers, combined with empirical data. In other words, it would be a matter of understanding the dynamics in social learning that potters used to spread their knowledge to others and how this learning process can be affected by geographical distance.

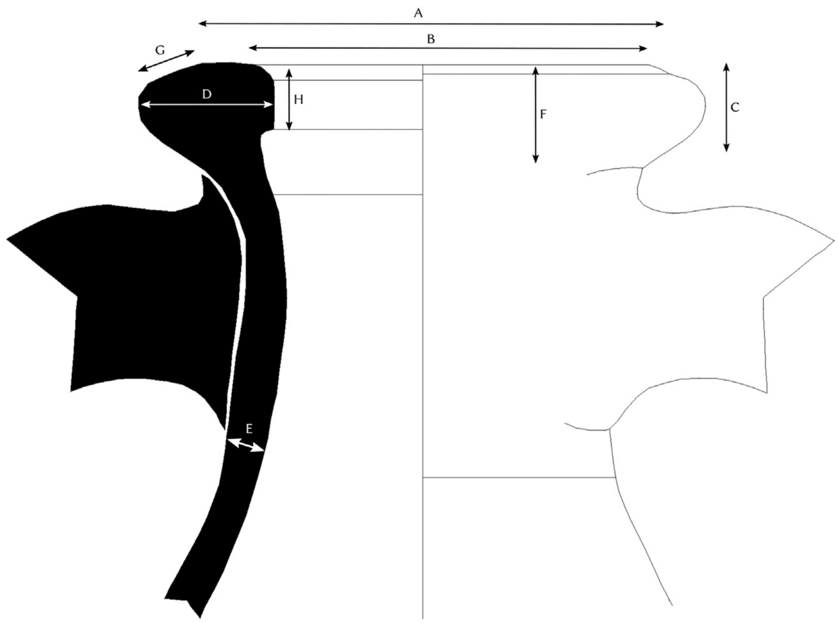

Fig. 2. Selection of the 8 measurements of each amphora Dressel 20 for the analysis (as referenced from Coto-Sarmiento et al. (2018) and Coto-Sarmiento and Carrignon (2023)). A: External diameter. B: Inside diameter. C: Rim height. D: Rim width. E: Shape width. F: Rim inside height. G: Rim width 2. H: Protruding rim. Further information on the analysis and results can be seen in Coto-Sarmiento et al. (2018).

3. Material and methods

3.1. Material

Three modes of cultural transmission are often used to explain human behaviour: vertical transmission where kinship influences (i.e. parents to offspring), oblique transmission where members of an earlier generation transmit knowledge to the younger generation (i.e. master to disciples) and horizontal transmission where the transmission occurs between individuals of the same generation (Cavalli-Sforza and Feldman, 1981; Boyd and Richerson, 1988; Acerbi and Parisi, 2006; Mesoudi, 2011, 2016). In this work, we focus on oblique and horizontal transmission, considering that it may not be perceptible at an archaeological level that such large-scale production is limited to contexts from parents to children.

For the model, we selected a sample of 470 olive oil amphorae (Dressel 20) from 5 different workshops used in Coto-Sarmiento et al. (2018). From this sample, we used a sample of 413 olive oil amphorae to compute the Mantel correlation coefficient used to compare our simulation. We then used a sample size of 470 amphora for each of which we analysed 8 measurements. The selected measurements can be observed in Fig. 2. From these 470 samples, we computed their mean, the maximal and minimal values these measurements could take, and a covariance matrix. The mean of the measurements is used to initialise the model, while the covariance matrix, as well as the minimal and maximal values, are then used in the model to constrain the way amphora can be produced. The mean will evolve depending on the transition action.

The selection of the measurements was mainly driven by three reasons: (a) rims are one of the most common indicators of variability in Dressel 20 and are the most preserved in archaeological excavations (Berni, 2008), (b) the aim of detecting variations or similarities acquired both intentionally or unintentionally in technical skills over centuries in the production of amphorae in each workshop (Carandini, 1979; Mannoni and Giannichedda, 1996) and (c) measurements used as empirical data to verify whether the results obtained could show similarities with the results obtained in previous studies (Coto-Sarmiento et al., 2018), while the design of the agent-based model was a way to detect the mode of transmission more predominant among workers.

The morphological measurements of the amphora rims are used in two distinct steps within the framework. First, we calculate the overall mean and the covariance matrix of these measurements by pooling data from all five workshops. These two statistical descriptors serve to define the initial value for the prototypical ancestral amphora at the start of the simulation. The covariance matrix, in particular, constrains how the 8 morphometric variables co-vary when new amphorae are generated throughout the model runs, ensuring that the simulated morphologies remain within a realistic multivariate shape space.

Second, the same morphometric data are used to evaluate the correspondence between the simulated results and the observed archaeological record. To do this, we compute a morphometric distance matrix between workshops using a pipeline that includes Principal Component Analysis (PCA) to reduce dimensionality, followed by Linear Discriminant Analysis (LDA) to maximise between-group differences, and a confusion matrix to quantify misclassification rates. We then compare this morphometric distance matrix to a geographical distance matrix (in kilometres between workshops) using a Mantel test (Mantel, 1967).

3.2. Model description

The model is composed of two main entities: (1) amphora workshops and (2) production techniques.

Amphora workshops. They are located in different geographical locations. The host workers produce amphorae at these locations. Each amphora is deposited where the workshop is located. They produce amphorae following a particular production technique specific to each workshop. It is worth mentioning that the dataset is characterised by a high degree of chronological uncertainty, as it is extremely difficult to determine with precision when each workshop began and ceased production. Given the lack of reliable temporal resolution, we treated the assemblages as time-averaged and directed our modelling approach toward spatial variation, while explicitly acknowledging the limitations this assumption entails.

Occasionally, they may independently modify this set of rules or learn technical skills from other workshops, representing the movement of people and ideas between workshops.

Production Techniques. They are a set of rules that allow workers to produce amphorae. In this model, these techniques are represented by three elements: a list of mean measurements, a list of limits, and a covariance matrix. The covariance matrix is shared among all the workshops, setting a universal "proportion rule" which dictates how the different elements of an amphora are correlated one with another. The list of means is unique to each workshop, representing the specific tools and techniques used by groups of workers within the workshop. The limits define structural boundaries, above or below which an amphora cannot be considered a valid amphora.

By following these rules, workshops produce amphorae that are slightly different from each other but remain, on average, specific to their workshop. This variation arises due to a combination of structural limitations and human-induced errors during the production process. Even when ateliers adhere to the same base structure for the amphora-building process, slight variations occur, reflecting individual worker techniques, workshop traditions, or minor inconsistencies in applying the rules. These modelled variations align with historical and archaeological evidence of amphora production, which applies equally to all workshops and will dictate how the measurements of the amphora are related and what the maximum and minimum sizes of these measurements can be. These constraints can be seen as physical properties that need to be respected to produce a useable amphora.

This is a very rough approximation of amphora production techniques. We derived the limits of each measurement from what was found in our dataset. This selection may not be realistic and strongly constrain the possible morphometries. Similarly, the use of a covariance matrix to dictate the relationships between the different elements of the amphora may be a very strong and simplifying assumption. First, it implies that all dimensions of the amphora are normally distributed. Second, it only very indirectly integrates the structural relationships between the different elements of the amphora. More complex models of tools-making techniques should be used. Dietrich Stout, for instance, proposes decision trees that could be represented as Genetic Programming models, in which the causal and hierarchical relationships between the different actions needed to construct artefacts are expressed (Stout, 2011). Specific knowledge about the mechanical properties of potteries (Gandon et al., 2011), as well as the way they are transformed during individual learning, should be added to precise the mutation processes roughly drafted here (Gandon et al., 2014, 2011).

The model design is detailed in Algorithm 1. It is split into two main phases: $INITIALISATION$ and $SIMULATION$. The latter is then also divided into two sub-parts: the production process and the cultural transmission processes.

During the $INITIALISATION$, all the entities described above (amphora workshops and techniques) are defined. Workshops are assigned a location given by the empirical evidence and common production technique using the measurement described in Section 3.1. At the initial stages, these production techniques are the same for all workshops.

During the $SIMULATION$, the workshop will produce amphorae and then, given parameters μ and α will modify or copy the production techniques.

In Algorithm 1 *Pop* is defined as the set of all workshops in the simulation. i is defined as the index of a specific workshop. P^i corresponds to the production techniques, while P^0 is defined as the initial production techniques, shared by all workshops at the initialisation stage. When the simulation starts, P^i will change depending on the innovation and copy mechanisms.

At the beginning of every time step, each workshop will 'produce' 20 amphorae. This is done by randomly generating 20 values from a multivariate normal distribution with means given by the list of means owned by the workshop and with a covariance matrix shared between all the workshops. The number of 20 amphorae has been chosen to give a relatively good sample of the underlying mean while preventing too much output.

In general, this production step is only important during the last time step, as it is the one we use to calculate the Mantel test. This is

Algorithm 1 General description of the model

```
INITIALISATION:
for i ∈ Pop do
    P^i = P^0
end for
SIMULATION:
for t ∈ 1tot_max do
    for i ∈ Pop do
        AmphoraProduction(P^i)
        X ~ U(0,1)
        if X < μ then
            P^i = Innovation(P^i)
        else
            P^i = RandomCopy(Pop, α)
        end if
    end for
end for
```

an important assumption: in our model, the important thing is to assess how workshops have diverged over time, observing the final production of each workshop and quantifying whether this final divergence can be attributed to geographic distance. This neglects an important part of the temporal aspect of the phenomenon. In the model, we assume that all workshops began production simultaneously and continue to do so in parallel, gradually diverging. In reality, some workshops may have been active later or may have ceased their activity. Therefore, some may have had less time to diverge than in the previous workshop. Considering the impact of the creation (or closure) of workshops in different periods is a crucial aspect of understanding changes in ceramic production and the standardisation of material culture in general. However, given the resolution of the available data and as a first attempt to apply the Cultural Evolution model to archaeology, we have decided to keep this simple model as a proof of concept and call for further similar work.

Once the production stage is finished, the workshop will *innovate* with a probability μ. This means the workshop will slightly modify its production techniques by randomly modifying the list of mean measurement that represents its actual production technique. The modification is done by adding or removing a normally distributed error of mean zero and standard deviation that depends on the measurement being modified. This standard deviation, which represents the strength of the modification, is set as two times the standard deviation observed in the whole dataset for each specific measurement. If the modification generates a mean that is too high or too small, concerning the range of known measurement, the modification is discarded.

With probability $1 - \mu$ (*i.e.* when the workshop does not innovate), they will copy other workshops based on α. The details of the copy mechanism are given in Section 3.3 below.

3.3. Experiment

We designed three different scenarios for the model. Each scenario represents one main mode of transmission (i.e. oblique, distance-dependent, and horizontal). Here, the aim was to assess the likelihood of replicating the correlation between the variability of amphora production for each workshop and the geographical distance between workshops, detected in Coto-Sarmiento et al. (2018).

For the simulation, we defined the probability for workshop i to copy the production techniques of workshop j as proportional to the distance d_{ij} between the workshops using the equation:

$$p(i,j) \sim e^{-\alpha d_{ij}} \tag{1}$$

where α is a parameter that allows for adjustment of the importance of the distance in the probability to copy (if α is small copy can be done regardless of distance, the bigger α is the harder it is to copy from a distant workshop). The distance $d_{i,j}$ between all pairs of workshops (i,j) has been computed using the river as a road connecting each workshop. These distances are symmetric, meaning $d_{ij} = d_{ji}$, which means we have not considered current or other geophysical phenomena that may have impacted the circulation on the river.

To transform this into a probability, we normalise it using:

$$P(i,j) = \frac{e^{-\alpha d_{ij}}}{K_i} \tag{2}$$

where

$$K_i = \sum_{j \in W} e^{-\alpha d_{ij}} \tag{3}$$

In reality, the actors of transmission are potters, who learn pottery methods from other potters. We implemented social processes at the workshop level. Thus, although in the model, when α changes, the probability that two workshops interact is changing, this should be interpreted as the probability for workers from these different workshops to interact. Based on that and different value of α, we defined three distinct scenarios that correspond to three type of social interaction.

3.3.1. Oblique transmission ($\alpha \to +\infty$)

In this scenario, the probability that two workshops copy each other is 0. In other words, workshops are isolated without contact with each other and the production techniques are exclusively shared within the workshop. This implies the absence of horizontal transmission, indicating that changes occur without the exchange of techniques between workshops, solely as a result of oblique transmission, where workers from one generation only learn from the workers from the same workshop from previous generations. This is shown by the red area and the green horizontal band on the right of Fig. 3.

The second scenario combines horizontal and oblique transmission with distance-dependent interactions. In this case, the probability of copying techniques depends on the spatial distance between the workshops. This represents scenarios where amphorae produced by closer workshops share more similar traits than amphorae produced by workshops further away. Workers in one workshop can learn and teach workers from other workshops, but are more likely to do so with a workshop closer in proximity. In that scenario the parameter α allows us to adjust this effect, thus describing a range of possible levels of distance-dependent interactions. It is represented by the area crossed by the yellow line in the middle of Fig. 3.

3.3.2. Horizontal transmission ($\alpha \to 0$)

This scenario represents situations in which workers in each workshop can interact and copy techniques with workers in other workshops without geographical restrictions. This allows a high degree of interaction between workshops active in the same periods, which is often also referred to as horizontal transmission. This scenario corresponds to the green area on the left of Fig. 3.

The Fig. 3 summarises these different scenarios in an idealised case.

The rest of the parameters are left fixed and are the same for all scenarios. They are described in Table 1. The measurements used to describe the amphora are given in Fig. 2.

3.4. Simulation

450 simulations were performed during 200 timesteps, the equivalent of 300 years of amphora production, for 100 values of α, logarithmically distributed between 0.0001 and 4, for a total of 45.000 simulations. This means that one time step is approximately the same as 1.5 years. All other parameters remain constant (cf Table 1).

For each simulation, a Mantel test is computed and the correlation obtained is stored; the results of these tests are given in the left panel of Fig. 4.

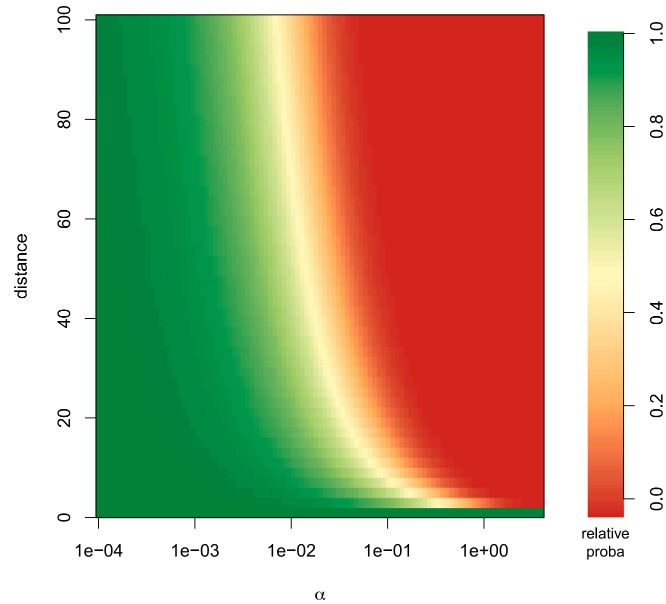

Fig. 3. Probability for a workshop to copy any other workshop change given α and the distance with the other workshop as per Eq. (1). Probability computed for a theoretical scenario where one workshop has neighbours regularly spaced between 1 to 100 km away. Red colour means a low probability of copying, while green colour represents a high probability of copying. Note that the colours represent *relative* probability. During simulations, these numbers are normalised following Eq. (2). This means that if a workshop has 11 neighbours with a relative probability of 1 then the likelihood of copying any of these neighbours will be the same: 1/11. If it has 1 neighbour with a relative probability of 1 and 11 with 0.1, the probability of copying the first will be 50% against 5% for the others. We can observe how, when α gets below 0.01, the workshop is as likely to copy any other workshop (horizontal transmission), whereas when α is above 0.5 it is only likely to copy itself (oblique transmission), with a wider range of option in between where distance plays a more or less important role (distance-dependent transmission). The horizontal green line at 0 shows that, regardless of α, the workshop always has a non-null probability of copying itself. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
General parameters of the model.

Variable	Description	Value
μ	Innovation rate	0.05
t_{max}	Length in time step	200
n_w	Number of worker per workshops	20
Pop	Workshops and positions	from data (cf. Fig. 1)
α	Impact of distance	100 values from 0.0001 to 4

From these results, the value of α yielding simulation with the correlations closest to the one observed in Coto-Sarmiento et al. (2018) is extracted and used to compute the expected probability of interaction between every workshop given by Eq. (2).

In this approach, we focus on understanding which specific values of α reproduce empirical observations by running multiple simulations. Although this method shares some similarities with Approximate Bayesian Computation (Kandler and Powell, 2018), and especially its rejection version, we chose not to define it as such. Firstly, we did not establish a comprehensive prior distribution for the model. Although one could derive it from our Table 1 it would be a combination of fixed parameter values and a discrete range of values resulting in a non-standard prior distribution that does not align with conventional ABC methodologies. We aimed for a simpler framing of our approach, focusing on which values of α most effectively mirror empirical Mantel correlation observations. Future work could include the implementation of a more comprehensive Bayesian framework, such as the Approximate Bayesian Computation (ABC). This would allow us to compute the full posterior of the model, and thus explore aspects of the problem that have not been explored in this study, although pointed by others as very important such as the rate and intensity of transmission (cf Chapter 4 of Porčić (2023)), that could be modulated through our $1-\mu$ parameters and the number of worker per workshop.

4. Results

The graphic on the left in Fig. 4 shows how R varies depending on the α parameters, and how the distance between workshops impacts cultural transmission. We can observe that when α is high (above 0.5), the median value of R does not change and stays close to zero: the correlation between morphometrics and workshop distances is purely random. This corresponds to the oblique transmission scenario, where there is no exchange between workshops, each evolving at its own pace depending on μ, also visible as the red area in Fig. 3. Similarly, when α becomes small enough, the median of R remains close to zero, showing no correlation between geographical distance and morphometries. This corresponds to the horizontal transmission scenario, where workshops exchange regardless of their distance (i.e. the green space on the left of Fig. 3). It is worth noticing that in this scenario, the range of R measured for the simulations is wider than for the oblique scenario one (wider interquartile ranges). This indicates that when cultural transmission is high, which is the case when there is no geographical limitation, the range of possible outcomes increases.

Between these two extreme scenarios a great variety of phenomena occurs; from slightly inversely correlated cases to strongly correlated ones. This corresponds to the space crossed by the yellow line on Fig. 3. The slightly inverse correlation could be explained by the fact that for small enough α (between 0.001 and 0.01), although workshops can virtually copy almost anyone, it is slightly more likely that nearby workshops copy each other. Thus, workshops with multiple not-to-far neighbours will have multiple sources of mutations: μ and their neighbours. On the other hand, the workshops located extremely far away will be less influenced by these two factors, thus retaining more of the initial similarity. This could lead to cases where more distant workshops exhibit greater similarity than closer ones, as they have undergone fewer changes since initialisation.

Then, as expected, when α is between 0.01 and 0.5, morphometric and distance become more or less correlated depending on α. This corresponds to our distant-dependent scenarios.

We then computed the distance between the mantel coefficients measured in the simulations with the coefficient observed in the real data and kept all the values of α for which this distance was below 0.05. On the left panel of Fig. 4, this corresponds to counting the simulations slightly below and above the red line. A Kernel estimation of this distribution is drawn on the right panel of Fig. 4.

The mode of this distribution, represented by the vertical dotted blue line, is 0.007. This shows the value of α for which our model is most likely to generate amphora measurements that correlate with the distance between the workshop, similar to what has been observed in the empirical data. This aligns with our distance-dependent scenario, where distance *does* matter while allowing relatively distant workshops to interact occasionally.

To illustrate what this mode of 0.07 exactly represents in terms of actual interactions between the workshops in the region studied, we computed the expected probability of interaction for every pair of workshops. To do so, we replaced α by 0.07 in Eq. (2) and the distance using the actual distance. The results are represented in Fig. 5. This figure clearly shows that, if there is a strong oblique transmission component – all workshops are always more likely to interact only with themselves than with another workshop – it is counter-balanced by a non-null, and relatively high probability that nearby workshops copy each other. Malpica, with a 60% likelihood of copying itself, is still expected to interact 40% of the time with Las Delicias or Cerro de Belén; workshops connected to it via the Genil River. Conversely, Cerro de Belén, located at the intersection of the Genil and Guadalquivir rivers, is equally likely to interact with Las Delicias and Villaseca, which are situated along different rivers. However, it is twice as likely to interact with Malpica, just a few kilometres away on the Genil River. On the opposite end of the spectrum, we observe that an isolated site like Parlamento is highly unlikely to interact with any other workshop due to its considerable distance. The same can be observed in the other workshops: if the rivers allow them to connect, they will interact with the other workshops, which are not far away, through this river connection. Otherwise, they are likely to remain isolated.

5. Discussion and conclusion

The agent-based model, in combination with empirical data, identified the types of cultural interactions that are likely to drive the diffusion of technology between amphora workshops in the *Baetica* province during the Roman Empire.

Our analysis suggests that some level of contact between workshops must occur to replicate what is observed in the empirical evidence. If workshops were completely isolated, as presented in the vertical transmission scenario in this work, the variation in morphometric traits would be higher than the observed variation. This may occur if the workshops had no contact with each other and independently modified their production techniques, leading to a greater divergence in technical processes. The simulation results indicate that this scenario could not have occurred in the observed region. Additionally, workshops, especially those along the Genil River, were likely to interact frequently.

On the other hand, our model shows that variation in the techniques between workshops may disappear when contact between workshops is not limited by geographical constraints. This could happen if workshops were extensively exchanging techniques and sharing skills; for instance, if the same group of workers were operating in all the workshops with the same tools and techniques. This would lead to faster and higher homogenisation, similar to what could be expected in a highly standardised production, regardless of the geographical distance. Our model suggests that this mode of transmission could not be realistic according to the empirical data. In the case of Parlamento, the furthest workshop shows a slightly different production compared to the others. Therefore, the acquired techniques will be more divergent depending on the geographical distance, being higher when the workshops are located in further locations (Coto-Sarmiento et al., 2018).

Based on the results of our analysis, the scenario most likely to reproduce empirical data corresponds to the scenario where technological exchanges exist but are limited by geographical distance. If people, techniques and tools were frequently moving from workshop to workshop, they were more likely to share more similar traits among workshops that were closer geographically. In our analysis, we notice the importance of the riverine connection in *Baetica* province for the amphora production. The proximity of the workshops to the rivers probably made this connection easier as production became increasingly standardised.

In general, despite being considered a highly standardised production, the methodology used in this work shows that the differences observed between workshops imply some degree of isolation due to geographical distance.

This process could be interpreted by a scenario where the learning process among potters would be from master to disciple in the workshop where they spent most of their time. Acquiring skills and knowledge involves learning from previous generations of workers, who then share the knowledge with subsequent generations (oblique transmission). Consequently, disciples are not unlikely to move to the closest workshops, to spread these techniques and teach them to the workers of these closest workshops. This will lead to amphora production, which tends to be more similar the closer the workshop is.

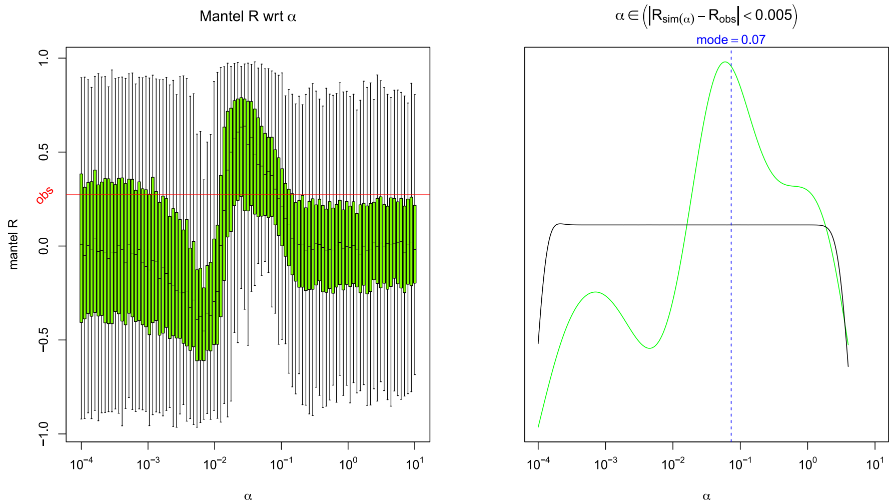

Fig. 4. Exploring the impact of α. All parameters except α are fixed. The left panel shows the Mantel R calculated between pottery measurements at the end of the simulation and the position of the workshop for all simulations for all different values of alpha. The red line represents the value of R computed from the real data in Coto-Sarmiento et al. (2018). The right panel shows a kernel estimation of the distribution of α for simulations where the difference between the R computed in Coto-Sarmiento et al. (2018) is less than 0.005. The vertical blue dotted line represents the mode of this distribution. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

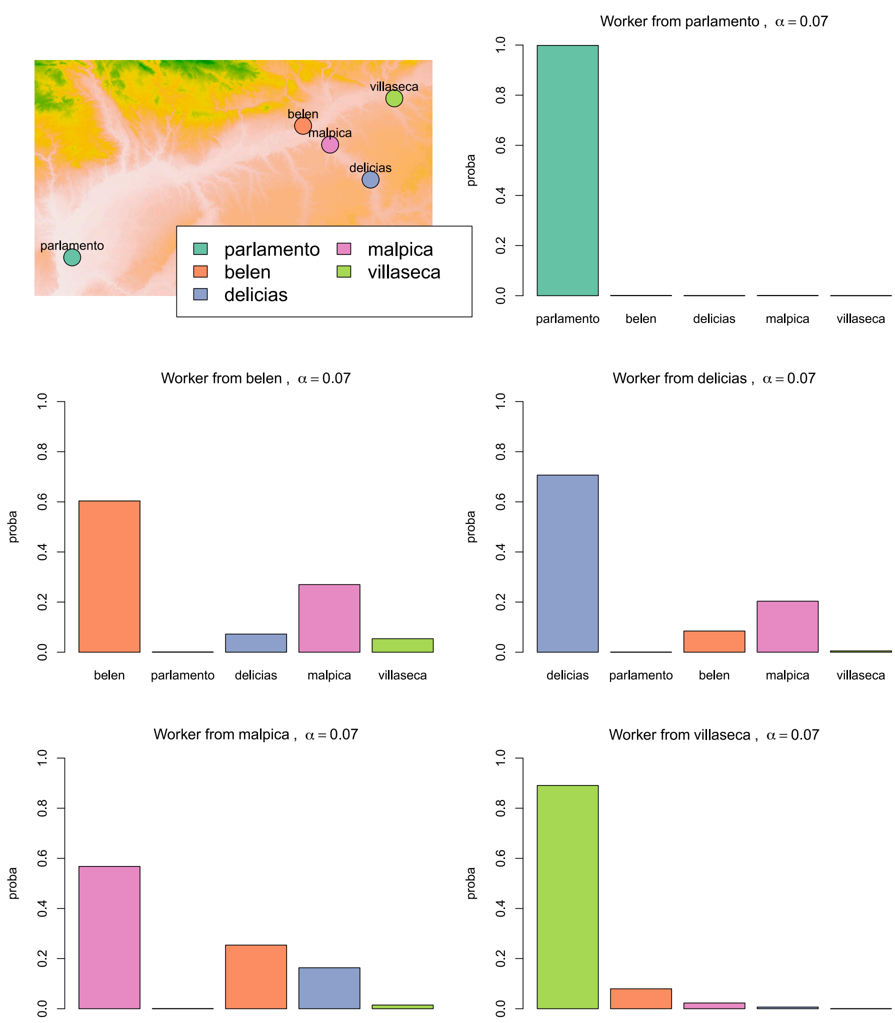

Fig. 5. Figure showing with which workers the workers of every workshop are more likely to interact when using $\alpha = 0.07$ (i.e. the mode of the posterior distribution found using simulation. For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

It is worth noticing that our results show a framework in a specific case study, and therefore, we do not discard that a horizontal transmission process influenced the context where high standardisation production was present. However, it seems that an oblique transmission context predominated in the first moment, generating a large progressive network of potters to exchange ideas and transmit knowledge to the closest workshops.

Our paper illustrates how the empirical data obtained and described in the previous study can be used in combination with Agent-Based Modelling to identify the cultural processes that drove the particularities in the morphology of the olive oil amphora despite few visible differences.

This work proposes a novel approach for archaeology to explore the process of learning transmission techniques underlying the production of material culture with a high level of standardisation. It shows that even when differences are imperceptible to the human eye, hypotheses can be formulated and tested regarding the underlying cultural processes that could explain these variations. We believe that this approach can be valuable for future research, not only in the context of pottery production in the Roman Empire but also for other periods where more industrialised production systems are in place.

CRediT authorship contribution statement

María Coto-Sarmiento: Writing – review & editing, Visualization, Writing – original draft, Methodology, Data curation, Formal analysis, Conceptualization. **Simon Carrignon:** Writing – review & editing, Visualization, Methodology, Writing – original draft, Software, Conceptualization.

Code and data availability

Data collection, data analysis, as well as the visualisation of the results of the simulations have been done with R (R Core Team, 2021). The model has been developed using Python (Van Rossum and Drake, 1995). Map was done by QGIS 3.30's-Hertogenbosch' with ESRI World Imagery (Clarity) Beta. Code, data and simulations' outputs are openly available as a Zonodo repository: https://doi.org/10.5281/zenodo.16541212.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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