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## MERCURY: an Agent-Based Model of Tableware Trade in the Roman East

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### Abstract

A large number of complex hypotheses exists that aim to explain aspects of the Roman economy, consisting of many explanatory factors that are argued to affect each other. Such complex hypotheses cannot be compared or tested through the traditional practice of qualitative argumentation and comparison with selected small sets of written and material sources alone. Moreover, these hypotheses often draw on different conceptual frameworks to abstract the same past phenomenon under study, hampering formal comparison. There is a need in the study of the Roman economy for more formal computational modelling for representing and comparing the many existing conceptual models, and for testing their ability to explain patterns observed in archaeological data where possible. This paper aims to address this need. It argues that communicating the potential contribution of computational modelling to scholars of the Roman economy should focus on providing theoretically well-founded arguments for the selection of the included and excluded variables, the conceptualisation used, and to address those elements of conceptual models that are at the forefront of scholarly debates. This approach is illustrated in this paper through MERCURY (Market Economy and Roman Ceramics Redistribution, after the Roman patron god of commerce), an agent-based model (ABM) of ceramic tableware trade in the Roman East. MERCURY presents a representation of two conflicting conceptual models of the degree of market integration in the Roman Empire, both of which serve as potential explanations for the empirically observed strong differences in the distribution patterns of tablewares. This paper illustrates how concepts derived from network science can be used to abstract both conceptual models, to implement these in an ABM and to formally compare them. The results of experiments with MERCURY suggest that limited degrees of market integration are unlikely to result in wide tableware distributions and strong differences between the tableware distributions. We conclude that in order for the discussion on the functioning of the Roman economy to progress, authors of conceptual models should (a) clearly define the concepts used and discuss exactly how these differ from the concepts used by others, (b) make explicit how these concepts can be represented as data, (c) describe the expected behaviour of the system using the defined concepts, (d) describe the expected data patterns resulting from this behaviour, and (d) define how (if at all) archaeological and historical sources can be used as reflections or proxies of these expected data patterns.

### Keywords:

Roman Economy, Network Science, Economics, Archaeology, Ceramics, History

### Introduction

- 1.1 The vast amounts of Roman pottery found on sites throughout the former Roman Empire are the archaeologist's main source of data used to investigate the functioning and performance of the Roman economy. However, so far the study of the Roman economy through pottery distributions has been dominated by exploratory data analysis and conceptual models (hypotheses). The undoubted complexity of the real past phenomenon that is the Roman economy and the many factors that played a role in its functioning and performance have led scholars of the Roman economy to focus on qualitative evaluation of models and comparison with selected small sets of written and material sources alone. There is an almost complete absence of applications or approaches that allow for different conceptual models to be formally compared or tested. There is a need in the study of the Roman economy for more formal computational modelling for representing and comparing the many existing conceptual models, and for testing their ability to explain patterns observed in archaeological data where possible. Moreover, the ability of this approach to evaluate many explanatory factors through experimentation and how it can contribute to ongoing qualitative debates

need to be illustrated.

- 1.2 This paper aims to address this need by presenting a computational modelling approach to the Roman economy and focusing on providing theoretically well-founded arguments for the selection of the included and excluded variables, the conceptualisation used, and to address those elements of conceptual models that are at the forefront of scholarly debates. We believe this approach and argumentation will facilitate communication of the potential of this approach to scholars of the Roman economy and enable it to make constructive contributions to ongoing debates.
- 1.3 This approach is illustrated in this paper through MERCURY (Market Economy and Roman Ceramics Redistribution, after the Roman patron god of commerce), an agent-based model (ABM) of ceramic tableware trade in the Roman East, developed to illustrate the potential of computational modelling for the study of the Roman economy. It aims to abstract aspects of two conflicting conceptual models of the functioning of the Roman trade system using comparable network science concepts. This paper places a strong emphasis on the conceptualisation and implementation of MERCURY, and additionally describes the sensitivity analysis measuring effects of changing independent variables on the resulting simulated tableware distributions (the dependent variable). A comparison of the simulated output of MERCURY with archaeologically observed tableware distribution patterns, as well as a more detailed discussion of the two conceptual models introduced briefly below, can be found in Brughmans and Poblome (2016).

## Explaining pottery distributions

- 2.1 The study of tableware distributions in the Roman Eastern Mediterranean between 25BC and 150AD offers a good example of the potential for computational modelling to push the study of the Roman economy forward. Four different wares (pottery produced from different clays in different centres or regions) produced in the Eastern Mediterranean in this period are assumed to be of regional and supra-regional importance, since they are found on many sites around the Eastern Mediterranean: Eastern Sigillata A (ESA), Eastern Sigillata B (ESB), Eastern Sigillata C (ESC), and Eastern Sigillata D (ESD). Of these four, however, only one is found in abundance on a significantly higher number of sites than the others: ESA. An exploratory analysis (Brughmans & Poblome 2016) reveals that ESA has by far the widest distribution until at least 75AD, i.e. ESA is attested at far more sites than other wares (Fig. 1). After 75AD its width of distribution gradually decreased, whilst the distribution width of ESB and ESD slowly increased in the period 50-125AD.
- 2.2 MERCURY was designed to study this pattern by addressing the following research questions: what hypothesised processes could give rise to this pattern? How does the availability of reliable commercial information to traders affect the distribution patterns of tableware?

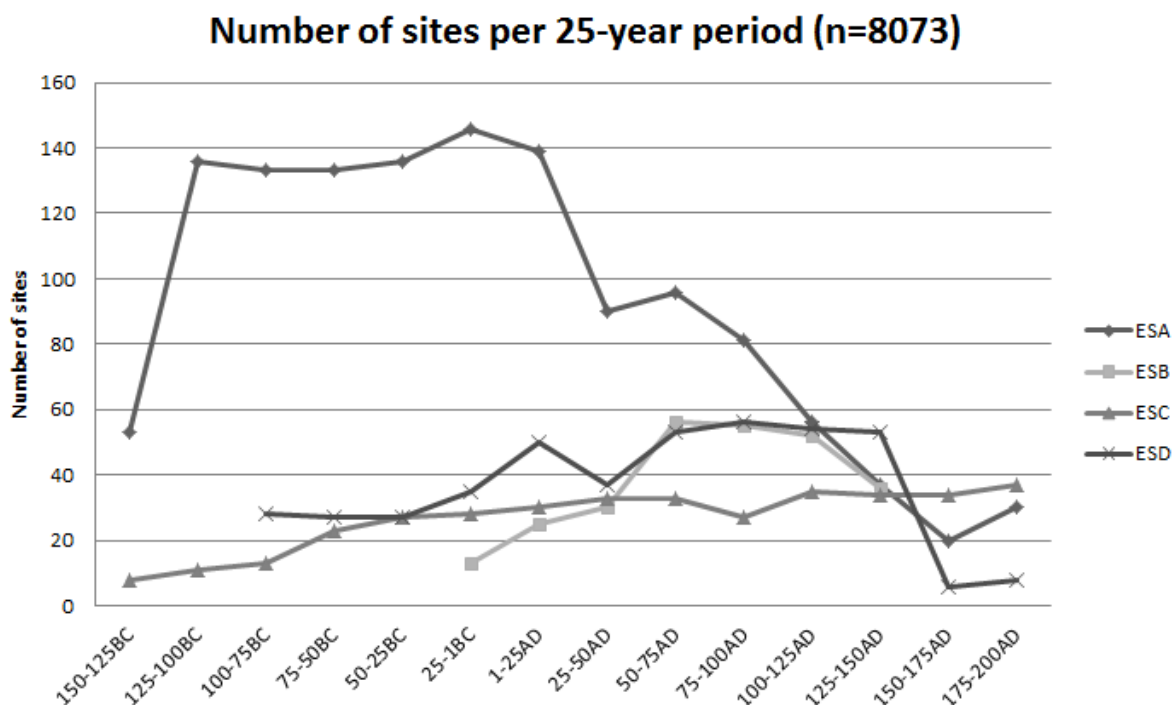


Figure 1. The number of sites each ware is attested at per 25-year period (data from the ICRATES database,  $n = 8073$  tableware sherds). This figure illustrates that ESA is attested on far more sites than the other three wares for the period of 150BC-75AD.

- 2.3 Archaeologists and historians have argued over a wide range of different conceptual models to explain this pattern in the tableware distribution (e.g. Abadie-Reynal 1989; Bang 2008; Bes 2015; Lewit 2011; Reynolds 1995). Although each author argues the Roman trade system was a complex system and agrees it consisted of a combination of driving forces, each author places an emphasis on different factors (e.g. state involvement, redistributive centres, consumption "pulling forces", commercial

"piggy-back" trade, closeness to large-scale agricultural production). However, the ability to compare different models in a strictly conceptual way, as thought-experiments, is limited due to a number of issues. Firstly, the existing conceptual models rarely abstract the complex past phenomenon that is the Roman trade system in terms of concepts more commonly used in economics or other disciplines that would facilitate comparison, or commonly used concepts and how these can be identified in the available sources are defined differently by different authors. Secondly, specifications for the kinds of data patterns one would expect to see as an outcome of different conceptual models (i.e. model predictions) are rarely provided.

- 2.4 To illustrate these issues and the potential of computational modelling for the study of the Roman economy, we will focus here on two conflicting conceptual models: Peter Bang's Roman bazaar (2008) and Peter Temin's Roman market economy (2013). Here we will focus in particular on the elements of these models that concern the flow of commercial information between traders. Bang suggests the Roman Bazaar concept to describe such flows: local markets distinguished by high uncertainty of information; relative unpredictability of supply and demand; communities of traders active on different markets were opportunistic and protectionist. In Bang's conceptualisation all of these factors led to poorly integrated markets throughout the empire characterised by a limited availability of commercial information between markets. Temin agrees with Bang that the information available to individuals was limited and that local markets are key structuring factors. However, contrary to Bang he believes that the Roman economy was a well-functioning integrated market where prices are determined by supply and demand. A key difference between both models is the degree of market integration, which represents the availability of commercial information (supply, demand, prices) to traders on different markets. Bang argues that different circuits for the flow of goods could emerge as the result of different circuits for the flow of commercial information. In other words, the observed distribution patterns of wares are a reflection of the functioning of past social networks between traders on different markets (Bang 2008, 288). Temin's model can be considered to offer an alternative, where the structure of social networks as a channel for the flow of commercial information must have enabled strongly integrated markets.

## Model description

- 3.1 We will first present a summary overview of the workings of the model. This will be followed by a description of how the conceptual models by Bang and Temin are abstracted using a conceptualisation that allows for comparisons between both, and how this conceptualisation is represented in MERCURY. We will then provide a technical description of the procedures used to initialise the model, and of the trade procedures used when the model is running. Finally, the design of the presented experiments and the selected parameter ranges are discussed. Variable names used in the model are in *italics*. Table 1 lists all independent and dependent variables included in this ABM with a short description and their tested or default value (excluding reporter and counter variables which are listed in Supplement 2).
- 3.2 These conceptualisations, representations, and procedures are implemented in an ABM coded in Netlogo v.5.0.5 using the 'network' and 'nw' extensions.<sup>[1]</sup> MERCURY and its documentation following the ODD (Overview, Design concepts, Details) protocol (Grimm et al. 2006; 2010) can be downloaded from the OpenABM repository (Brughmans & Poblome 2015).

### Model overview

- 3.3 The MERCURY model represents the structure of social networks between traders that act as the channels for the flow of commercial information and goods. The model is initialised by creating a social network between traders who are distributed among sites. Four of these sites are production centres. Each of them produces one of the four different wares, and traders located at these sites obtain a number of items of this locally produced ware in each turn. At each time step traders will determine the local demand for tableware they want to satisfy, and will estimate the price they believe an item of tableware is worth based on their knowledge of the supply and demand of the traders they are connected to. Every item of tableware is then put up for sale, and pairs of traders who are connected in the network can buy or sell an item. When an item is successfully traded, the buyer will decide to either sell it to a local consumer to lower the demand (in which case the item is taken out of the trade system and is deposited at that site), or to store it for redistribution in the following turn in case this promises a higher profit. Over time, this model therefore gives rise to distributions of four tablewares which can be compared to the archaeological data.

### Conceptualisation and representation

- 3.4 The social networks described by Bang consist of a strong community structure within markets, limited availability of commercial information between communities, and weakly integrated markets. The system described by Temin consists of limited availability of commercial information, and well integrated markets where prices are determined by supply and demand. The terms in **bold** are concepts these authors use to abstract their ideas about Roman trade, and need to be clearly defined before their implementation in computer code. The social network aspects of the models by Bang and Temin can be usefully conceptualised and represented as follows (the most fundamental concepts are introduced first, followed by more elaborate concepts that build on the definitions of the fundamental concepts):

- **Commercial actors.**  
Conceptualisation: these have agency and are here referred to as traders. No differentiation is made between types of traders, other than the ability to trade within a market and/or between markets, depending on the network neighbours of the trader.

Representation: software agents represented as nodes.

- Markets.

Conceptualisation: places where traders come together, where different communities of traders exist, and where tableware and commercial information are available. We decided to use the archaeological term "sites" in this paper and in the ABM code to refer to our representation of the markets discussed by Bang and Temin, for two reasons: to avoid equating the past phenomenon under study (the Roman market economy) with the approach (ABM) and data (archaeological finds) we use to study it; and to facilitate comparison between the simulated distributions and the archaeologically observed pottery distributions (referred to by archaeologists as the assemblages excavated at sites). Representation: a location in abstract space on which a set of traders is located. All traders are distributed among all sites. Tableware is deposited on sites through trade procedures, and these simulated deposits can be compared to excavated deposits at archaeological sites.

- Product.

Conceptualisation: one of four tablewares.

Representation: four tablewares are here referred to as four products (A, B, C, D). Each product is produced at a different site. Units of each product are exchanged between traders through trade, and are deposited at sites. Each product is valued equally by traders, since we assume consumers obtain tableware for functional rather than aesthetic or other purposes. MERCURY is not designed to test alternative valuations.

- Supply.

Conceptualisation: the amount of tableware a trader owns and is willing to sell.

Representation: the amount of tableware each trader owns at the start of each time step.

- Demand.

Conceptualisation: here used as the demand for tablewares of consumers at a site a trader is aware of and is able to supply for.

Representation: *Demand* is a variable of traders. Demand can only be satisfied by obtaining an item of any product through a successful transaction between a pair of traders. It is assumed here that each trader has the ability to supply at most for a fixed maximum demand in each time step, determined by the independent variable *max-demand*. MERCURY is not designed to test traders with variable abilities to satisfy demand.

- Commercial information.

Conceptualisation: the knowledge a trader obtains of supply and demand.

Representation: traders obtain the values of supply and demand from a proportion of the traders they are connected to and use it to estimate the price they believe tableware is worth within their part of the social network.

- Social network.

Conceptualisation: traders have the ability to share commercial information and tableware with other traders they are directly connected to in a social network.

Representation: a non-directed edge between a pair of nodes represents the ability to share tableware and commercial information between this pair of nodes. The set of all nodes and the set of all edges constitute the social network.

- Limited availability of information.

Conceptualisation: only a proportion of the traders a trader is able to trade with shares commercial information with that trader.

Representation: the proportion of a node's neighbouring nodes in the social network of which it knows the supply and demand. The variable *local-knowledge* is used to implement this proportion in the code, one of the dependent variables of the model tested in experiments. A low value of this variable represents limited availability of accurate commercial information (as both Bang and Temin argues was the case in the Roman trade system).

- Community structure.

Conceptualisation: communities consist of traders who are more likely to trade and share commercial information with each other.

Representation: a social network structure with a high clustering coefficient within sites, and with a lower number of links between clusters than within clusters. In other words, the social network of traders within each site will have a 'small-world' network structure with a high clustering coefficient and a low average shortest path length (Watts & Strogatz 1998).

- Market integration

Conceptualisation: the ability to share commercial information and goods between markets.

Representation: the proportion of all possible edges between nodes that connect nodes on different sites. This proportion is tested by varying the variable *proportion-inter-site-links* in experiments. A high value for this variable represents highly integrated markets (as suggested by Temin), a low value represents weakly integrated markets (as suggested by Bang).

- 3.5 A final important factor is the conceptualisation of time in the model. In archaeology, the accuracy of dates is often problematic. The lower and upper limits of how long an item of tableware remained in use vary greatly, as shown by Peña (2007) in his model of the use-life of this type of pottery. Moreover, as illustrated by Willet's (2012, 44–46) calculation, these are only estimates and they suggest extreme differences in the volumes of tableware in circulation in the Eastern Mediterranean during the study period. In this model we therefore decided to work with a relative 'transaction time' rather than an absolute timeframe: the time of each time step is the time it takes for all tableware available for trade to be considered in a transaction, and the demand to increase by

one item per trader if it is not at its maximum.

#### Initialization procedures

- 3.6 The model is initialized in three steps, in this order: creating sites and traders, distributing the traders among the sites, and connecting traders in a network (Figure 4 presents a flowchart of the initialization).

#### *Creating sites and traders*

- 3.7 A set of sites and a set of traders are created determined by the variables *num-sites* and *num-traders* respectively. The numbers of sites and traders do not change throughout an experiment. Sites are positioned in a circular layout, which is convenient for setting up the social network and for visualisation, but the network is the only means of determining proximity between sites. The model is not spatial as it does not represent the geographical distribution of sites. Four sites, equally spaced along the circle, are selected to become production sites of one of four products each.

#### *Distributing traders*

- 3.8 When *equal-traders-production-site* is set to 'true', an equal number of traders (determined by the variable *traders-production-site*) is moved to each production site. The remaining traders are then distributed on the other sites following a uniform or exponential frequency distribution, depending on the setting of the variable *traders-distribution*.
- 3.9 When *equal-traders-production-site* is set to 'false', all traders are distributed among all sites (i.e. including the production sites) following a uniform or exponential frequency distribution, depending on the setting of the variable *traders-distribution*.
- 3.10 The mean of the exponential frequency distribution is the number of traders that have not yet been moved to a site divided by the number of sites.
- 3.11 The exponential frequency distribution will result in strong differences between the number of traders per site, where a few sites have a very high number of traders and most sites have a much lower number of traders. Since the maximum demand of a site in this model is determined by the number of traders present at a site, this exponential distribution of traders is considered to reflect the differing demands of markets throughout the Mediterranean: markets with an extremely high demand are relatively rare (e.g. in the cities of Alexandria, Antioch, Ephesos) whilst most markets will have a much more modest demand. A uniform frequency distribution of traders is considered unrealistic, but is included as a benchmark to compare its outputs with that of experiments with an exponential frequency distribution.

#### *Creating the social network*

- 3.12 Traders are subsequently connected to each other to form a social network with a structure that represents the hypotheses tested by setting the variable *network-structure* to the value "hypothesis" (this variable can also be set to "random" in order to compare the results of experiments to those of an experiment with a graph created through a random process with the same density). This hypothesised structure, as mentioned above in section Conceptualisation and representation is considered to have a high clustering coefficient within sites, relatively few links between clusters within sites, and a modifiable proportion of links between sites. It was decided to use the 'small-world' network structure as a baseline for creating this hypothesised network within sites, and to combine this with a variable that allows for modifying the proportion of links between sites (*proportion-inter-site-links*). The procedures to create a social network in MERCURY are based on the initialisation procedures of the model for the growth of social networks with a 'small-world' structure by Jin, Girvan and Newman (2001; referred to in Jin et al. 2001 as Model II), which has previously been applied in an archaeological model of exchange by Bentley, Lake and Shennan (2005). The simplified version of the model was selected because it gives rise to the network structure of interest (maximum degree, low average shortest-path length, high clustering coefficient) with relatively few parameters. MERCURY's network creation procedures consist of five steps (see Fig. 2; Supplement 1 includes the number of edges created in each of these five steps for each experiment):

- Firstly (Fig. 2a), between each pair of neighbouring sites on the circular layout, one pair of randomly selected traders located on neighbouring sites is connected. This ensures a minimum of connectivity between sites that allows for goods to still be distributed to all sites. In scenarios where no other inter-site links are added, information and goods will therefore need to travel from site to site along the circular layout.
- Secondly (Fig. 2b), a number of inter-site links is created. A proportion (determined by the variable *proportion-inter-site-links*) of all trader pairs are connected if a pair is not located on the same site and is not connected yet. The total number of trader pairs is calculated as:

Calculation of total number of trader pairs:

$$\frac{1}{2}N(N-1) \quad (1)$$

where  $N$  is the total number of traders. This step therefore allows us to test different degrees of market integration, by increasing or decreasing in experiments the proportion of edges between traders on different sites.

- Steps three and four will result in a 'small-world' network structure within sites, where clusters exist that have few connections between clusters. These steps are adopted from the model by Jin et al. (2001). Thirdly (Fig. 2c), randomly selected pairs of traders on the same site are connected. More formally, a proportion of all trader pairs determined by the variable *proportion-intra-site-links* are connected if they meet the following requirements: both are located at the same site, the pair is not connected yet, and neither of the traders has the *maximum-degree*.
- Fourthly (Fig. 2d), pairs of traders on the same site with a mutual neighbour in the network will be connected. This step is responsible for the high level of clustering and is a process common in social networks called transitivity, which stands for the idea that a pair of individuals who have a mutual friend have a high probability of becoming friends themselves in the future. The step is implemented as follows: a number of traders are selected uniformly at random; the number of selected traders is a proportion of all trader pairs with a mutual neighbour (the proportion is determined by the variable *proportion-mutual-neighbors*, and the number of trader pairs with a mutual neighbour is calculated as in eq. 2); if these randomly selected traders are connected to a pair of traders on the same site that are not connected yet and do not have the *maximum-degree*, then such a pair of traders of whom the randomly selected trader is a mutual neighbour will be connected. Equation 2 shows the calculation of all trader pairs with a mutual neighbour:

Calculation of all trader pairs with a mutual neighbour:

$$\frac{1}{2} \sum_i z_i(z_i - 1) \quad (2)$$

where  $z_i$  is the degree of the  $i^{\text{th}}$  trader. Steps three and four of this network creation procedure are repeated while the average degree of the network is lower than *maximum-degree* minus 10%, a point at which those traders who do not have a maximum degree cannot create any further links without violating the rules of steps three and four (our implementation of the requirement in Jin et al. (2001, 7) for "all or most" traders to have a degree close to the maximum). The default values for the variables in steps three and four were adopted from Jin et al. (2001) and, within each site, result in a 'small-world' network structure of traders.

- Fifthly (Fig. 2e), at this stage the network can still consist of multiple components, i.e. there exist subsets of nodes, where nodes within subsets can be connected but there are no edges between the subsets. This would prohibit tableware produced in one area of the network to reach traders in another. Therefore, a minimum number of edges are added between pairs of traders on the same site which are not in the same component, to ensure all traders become part of a single component. This generally results in very few extra links being created (between 2 and 19 in the experiments presented here) and has a minimal impact on the 'small-world' structure of the networks within sites.

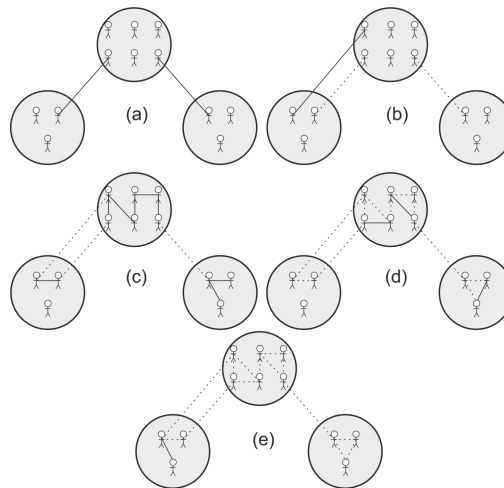


Figure 2. Abstract representation of the five-step procedure (a-e) used to create the hypothesised network structure. Traders are represented as stick figures and are distributed among sites represented as circles. Newly created edges are represented as solid lines, dashed lines represent existing edges. (a) a pair of traders on each pair of neighbouring sites is connected; (b) randomly selected pairs of traders on different sites are connected; (c) randomly selected pairs of traders on the same site are connected; (d) pairs of traders on the same site with a mutual neighbour are connected; (c) and (d) are repeated until all or most traders have the maximum allowed number of connections; (e) a minimal number of randomly selected traders in different components on the same site are connected. Note the final network structure (e) consists of clusters of traders on sites, a limited number of edges between clusters, a proportion of edges between traders on different sites, and a single connected component.

- 3.13 The result is a network structure where neighbouring sites are connected by at least one edge between a pair of traders, where traders within the same site are connected in clusters with few connections crossing clusters, and with a variable number of inter-site links depending on whether Bang's or Temin's hypothesis is being tested (Fig. 3), and all traders being part of a single

connected component. Traders on each site are therefore connected following a 'small-world' network structure (Watts and Strogatz 1998), with a high clustering coefficient and a low average shortest path length. However, the overall network structure of all traders on all sites combined will not always show the characteristics of a 'small-world' network, since the number of inter-site edges added in addition to the edges connecting traders on neighbouring sites is determined by the variable *proportion-inter-site-links* used to represent different degrees of integration of markets (see Supplement 1).

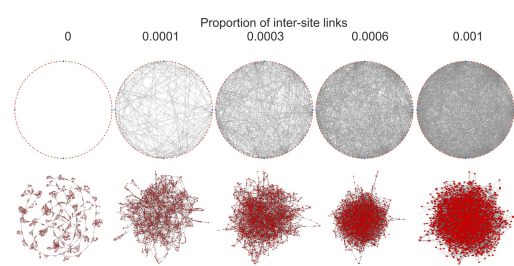


Figure 3. Example of the network structure generated in the setup procedure of MERCURY showing the resulting networks for different values of the *proportion-inter-site-links* variable. The top row shows a network of sites layed-out along a circle with traders positioned at sites. The bottom row shows the same networks but nodes now represent traders and the traders' social network laid-out using a force-directed layout algorithm (yFiles Organic layout in the network science software Cytoscape) to display its structure. Note the existence of clusters of traders on sites connected to few other clusters when the proportion of inter-site links is low (extreme left), a pattern which gradually disappears as traders receive more inter-site links and the sites become more integrated.

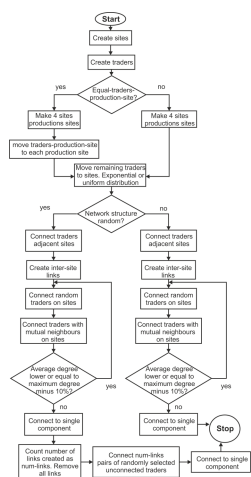


Figure 4. Flowchart of initialization procedures in MERCURY.

### Trade procedures

- 3.14 In every time step of the model the trade procedures follow these steps: 1) all traders determine demand, 2) they discard part of their stock, 3) traders on tableware production sites obtain new items, 4) all traders obtain commercial information, 5) they determine what they believe to be the current price for a tableware item, 6) they determine the maximum amount of items they are willing to stock in that time step, and finally 7) all items owned by all traders and not in stock are traded. Each step will be described in detail in the next subsections (Figure 5 presents a flowchart of the trade procedures).

### Determining demand

- 3.15 The *demand* of each trader is 0 at the start of the simulation. At each time step, a traders' *demand* is increased by 1 if his *demand* is lower than the trader's maximum demand determined by the independent variable *max-demand*. In other words, when a consumer obtains an item they do not immediately require a new one and at some point the inhabitants of a site do not require any more tableware. Instead, the demand gradually increases to the maximum. This mirrors the background microprocesses of losing, or breaking an item of tableware, of items becoming unfashionable with time, or any other microprocesses that result in the renewed need for the item. The total demand at sites will therefore reflect the distribution of traders among sites: the summed maximum demand per site will be equal for all sites in case of a uniform distribution of traders among sites, and will show strong differences in case of an exponential distribution of traders among sites. However, the total sum of maximum demand in the model for experiments with the same number of traders will always be the same, which facilitates comparison of experiment results.

### Discard part of stock

- 3.16 The ability for goods to be redistributed is key in both Bang's and Temin's conceptual models of the Roman trade system and is implemented in MERCURY by allowing traders to stock products. In the previous time step products can be put in stock as a

result of either a failed transaction or a deliberate storing of the item for redistribution in the next turn (see Trade products below). At the start of a time step traders who have stock will need to discard a fixed proportion of it. This penalty reflects the risks involved in not immediately selling an item on to a consumer but storing it for redistribution and represents broken or unfashionable items. The remainder of the stock is then considered for trade in the rest of this time step. The proportion of discarded items is set to 14%, which is a proportion suggested by Peña's (2007, Fig. 11.5) model for the life cycle of tableware distributed beyond the local area of its manufacture.

#### *Production*

- 3.17 Traders located on sites that were selected in the setup procedures as the production sites will obtain newly produced items each time step, only if their total current possession of all four products is less than their *demand*. If this is the case then they obtain items of the product being produced at that site equal to their *demand* minus the sum of the products they already possess i.e. they obtain the number of items needed to reach their *demand*.

#### *Obtaining commercial information and price-setting*

- 3.18 Once every time step, and before trade happens, a proportion of a trader's neighbours in the social network will be randomly selected as the trader's informants. From this proportion of neighbours the trader will know the *demand* and the sum of all items of all products they own (i.e. their supply). This proportion is determined by the independent variable *local-knowledge* and is used in the experiments to test scenarios with differing availability of information (together with the *proportion-inter-site-links* variable). The trader then calculates the average demand and average supply of this proportion of neighbours, including his own supply and demand. Using this commercial information available to him he then determines what he believes is the price of one item of any product as follows:

$$price = \frac{average\ demand}{average\ supply + average\ demand} \quad (3)$$

- 3.19 This results in a float value normalised between 0 and 1 following the logic of supply and demand: if the average demand is equal to the average supply then the price will be 0.5; if the average demand is higher than the average supply then the price will be between 0.5 and 1; if the average demand is lower than the average supply then the price will be between 0 and 0.5.

#### *Determine maximum stock*

- 3.20 The traders will subsequently determine how many items they are happy to store for redistribution in the next turn. For each trader the *maximum-stock-size* dependent variable is calculated as the average of the *demand* of the other traders he knows commercial information of, minus his own *demand*, rounded. The maximum stock is only higher than 0 when the average *demand* is higher than his own *demand*, i.e. when the trader believes there is a high *demand* which promises higher profits (because his own *demand* is lower) he will be willing to store the number of items necessary to supply for the average *demand*.

#### *Trade products*

- 3.21 Each item of every product is considered for trade once per time step. A single item is selected at random and the trader who owns it will consider selling it individually. An item is put in the trader's stock if he cannot make a profit or if none of his neighbours in the network require an item (i.e. their *demand* equals 0). An item is sold to a buyer if the buyer's *price* offers a profit or break-even for the seller. A seller will therefore only agree to sell tableware for more or the exact amount he estimates it is worth, and a buyer will only buy tableware for less or the exact amount he estimates it is worth (this means that there is no formal procedures for negotiation of prices and market clearance, a simplification introduced because MERCURY is designed only to evaluate the impact of differential availability of commercial information).
- 3.22 The buyer either places the obtained item in stock for redistribution if the average *demand* is higher than his *demand* (i.e. redistribution holds the promise of a higher profit), or if this is not the case he deposits it on his site (this action represents the trader selling the item to a consumer and the item leaving the trade cycle). In the latter case the buyer's *demand* is decreased by 1 because some of the local consumers' demand is satisfied; the item is taken out of the trade system because the consumer does not redistribute it; and it is deposited on the buyer's site (the site's dependent variable for that product (*volume-A*, *-B*, *-C*, or *-D*), is increased by 1).
- 3.23 This sequence of procedures results in distribution of four different products representing tablewares on sites. The volume and diversity of tableware deposited on sites can subsequently be used to compare the simulated tableware distribution with the archaeologically attested one (see Brughmans & Poblome 2016).



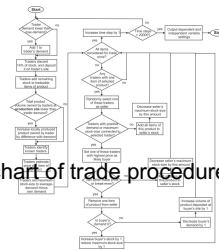


Figure 5. Flowchart of trade procedures in MERCURY.

## Experiments and variable settings

3.24 MERCURY allows us to compare and provide predictions for the conceptual models of Bang and Temin by changing the degree of market integration (i.e. the proportion of edges between traders located on different sites, controlled by the *proportion-inter-site-links* variable) and by changing the availability of commercial information (controlled by the *local-knowledge* and *proportion-inter-site-links* variables). A number of other independent variables are changed in separate experiments to explore different social network structures and trade procedures. Supplement 1 lists each experiment's settings for the independent variables, summary network measures for the resulting network structure, and summary statistics for the simulated distribution of products. Experiments were designed to explore the effects of changing the following independent variables:

- Changing the proportion of all trader pairs that are connected and are not located on the same site from 0%, to 0.01%, 0.06%, 0.1%, 0.2% and 0.3% (i.e. changing the *proportion-inter-site-links* variable);
- changing the proportion of neighbours a trader can obtain commercial information from between 10%, 50% and 100% (i.e. changing the *local-knowledge* variable);
- replacing the hypothesised social network structure with a randomly created network structure with the same density (i.e. changing the *network-structure* variable);
- varying the number of traders located at production sites in a range between 1 and 30 (i.e. changing the *traders-production-site* variable);
- changing the distribution of all traders at all sites between uniform and exponential (i.e. changing the *traders-distribution* variable);
- varying the maximum demand of traders in a range between 1 and 30 (i.e. changing the *max-demand* variable).

3.25 In these experiments, the independent variables listed in Table 1 are hypothesised to cause the differences in the volume and diversity of products deposited at sites (dependent variables), and once their values are set during the initialisation of the model they will not change during an experiment. The dependent variables (Table 1) dynamically change throughout the simulation as a result of the simulated trade procedures. The model outputs are the values of the dependent variables at the end of an experiment, i.e. the simulated volume of each tableware at sites. The output allows us to derive the diversity of products at sites and the wideness of products' distributions. The latter output in particular can be compared with the distributions of tablewares in archaeological datasets. The default values used in the experiments presented here for a number of independent variables are further discussed in Supplement 2. Each experiment was run for 20,000 time steps, a decision made in the absence of a realistic conceptualisation of time as described above, motivated by the observation that the wideness of wares' distributions (the pattern of interest in this study) stabilises the first 5000 time steps, and remains more or less fixed for the remaining time.

Table 1: Independent and dependent variables used in MERCURY, with a short description and the values used in experiments. See Supplement 2 for a similar list which additionally includes all counter and reporter variables, and a motivation for the selection of a default value in experiments for a number of independent variables.

Independent variables		
Variable	Description	Tested values
Global variables		
num-traders	The total number of traders to be distributed among all sites	1000
num-sites	The total number of sites	100
equal-traders-production-site	Determines whether the number of traders at production sites will be equal and determined by the variable 'traders-production-site' or whether it will follow the same frequency distribution as all other sites determined by the variable 'traders-distribution'	true, false
traders-distribution	Determines how the traders are distributed among the sites	exponential, uniform
traders-production-site	Determines the number of traders located at production sites if 'equal-traders-production-site' is set to 'true'	1, 10, 20, 30
network-	Determines how the social network is created when initialising an	hypothesis,

structure	experiment: a randomly created network, or the network structure hypothesised by Bang or Temin.	random
maximum-degree	The maximum number of connections any single trader can have	5
proportion-inter-site-links	The proportion of all pairs of traders that are connected in step two of the network creation procedure by inter-site links	0, 0.0001, 0.0006, 0.001, 0.002, 0.003
proportion-intra-site-links	The proportion of all pairs of traders that are considered in step three of the network creation procedure to become connected by intra-site links	0.0005
proportion-mutual-neighbors	The proportion of all pairs of traders with a mutual neighbour that are considered for becoming connected in step four of the network creation procedure by intra-site-links	2
Site-specific variables		
production-site	Set to "true" if the site is a production centre of one of the products	true, false
producer-A	Set to "true" if the site is the production centre of product-A	true, false
producer-B	Set to "true" if the site is the production centre of product-B	true, false
producer-C	Set to "true" if the site is the production centre of product-C	true, false
producer-D	Set to "true" if the site is the production centre of product-D	true, false
Trader-specific variables		
max-demand	The maximum demand each trader aims to satisfy	1, 10, 20, 30
local-knowledge	The proportion of all link neighbours a trader receives commercial information from (supply and demand) in each turn	0.1, 0.5, 1
Dependent variables		
Variable	Description	
Site-specific variables		
volume-A	The number of items of product A deposited on the site as a result of a successful transaction	
volume-B	The number of items of product B deposited on the site as a result of a successful transaction	
volume-C	The number of items of product C deposited on the site as a result of a successful transaction	
volume-D	The number of items of product D deposited on the site as a result of a successful transaction	
Trader-specific variables		
product-A	The number of items of product A the trader owns and can trade or store in this turn	
product-B	The number of items of product B the trader owns and can trade or store in this turn	
product-C	The number of items of product C the trader owns and can trade or store in this turn	
product-D	The number of items of product D the trader owns and can trade or store in this turn	
stock-A	The number of items of product A the trader puts in his stock in this turn as a result of an unsuccessful transaction or for redistribution in the next turn	
stock-B	The number of items of product B the trader puts in his stock in this turn as a result of an unsuccessful transaction or for redistribution in the next turn	

stock-C	The number of items of product C the trader puts in his stock in this turn as a result of an unsuccessful transaction or for redistribution in the next turn
stock-D	The number of items of product D the trader puts in his stock in this turn as a result of an unsuccessful transaction or for redistribution in the next turn
maximum-stock-size	The number of items the trader is willing to obtain through trade this turn in addition to his own demand if the average demand is higher than his demand
price	The price the trader believes an item is worth based on his knowledge of supply and demand on the market
demand	The proportion of the demand at the market the trader is located at that he aims to satisfy by obtaining products through trade. Constant increase of 1 per turn; maximum = max-demand

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## Results

- 4.1 As discussed in the introduction, the research question that motivated the creation of MERCURY is: under what conditions does the model give rise to one product being much more widely distributed than the three other products? This pattern is here studied through two measures: the number of sites at which each of the four products was deposited in experiments (referred to as the width of a product's distribution), and the maximum number of sites a ware is deposited on minus the minimum number of sites another ware is deposited on per iteration of each experiment (referred to as the range of distribution). In order to assess whether an experiment approximates the pattern observed in the archaeological record we evaluate whether it shows a high range of distribution and whether on average one product has a higher width than others, i.e. one product is deposited on far more sites than others.

### Number of edges

- 4.2 The setup procedure of MERCURY results in a static network structure with different proportions of edges between traders located on different sites depending on the setting of the *proportion-inter-site-links* variable. However, the total number of edges is similar in all experiments, with small variations due to the stochasticity (built-in randomness, see the ODD for a list of stochastic processes) in the model (Table 2, see also Supplement 1 for all experiments). Thus an increased proportion of inter-site edges results in a lower number of randomly created intra-site edges (step 3) and, in particular, intra-site edges between traders with a mutual neighbour (step 4). The latter is caused by the decreasing number of trader pairs on sites that have a mutual neighbour as the value of *proportion-inter-site-links* is increased. The tested values for *proportion-inter-site-links* range from 0%, to 0.01%, 0.06%, 0.1%, 0.2% and 0.3% of all trader pairs (see Table 2, in grey and underlined), resulting in almost no market integration to 100% market integration where all links are between trader pairs on different sites (see Table 2, in bold and underlined). These different degrees of market integration strongly affect the overall structure of the network as shown by the network measures in Table 2: both the clustering coefficient and the average shortest path length decrease considerably with an increase in market integration.
- 4.3 The social networks created in MERCURY are therefore very different depending on the degree of market integration selected in experiments: in scenarios with low market integration there will be strong clustering within markets (representing communities) but the shortest paths between trader pairs will be long (e.g. experiment 1) representing the conceptual model of Bang. On the other hand, in scenarios with high market integration there will be very limited clustering within markets but short paths between all trader pairs as proposed by Temin. A graph created through a random process with the same density (i.e. number of edges divided by the number of traders) and consisting of one connected component represents almost no clustering within markets and almost complete market integration (e.g. experiment 35).

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Table 2: The number of edges created in each step of the setup procedure for selected experiments representing different degrees of market integration (i.e. different values for the variable *proportion-inter-site-links* in grey and underlined). The total proportion of inter-site edges is the sum of steps 1 and 2 divided by the total number of edges in the network, results are shown in bold and underlined. Some variable settings for experiment 35 are presented in brackets, because in this experiment a randomly created network is considered with the same number of edges as the equivalent hypothesised network structure with the same variable settings. (exp. = exponential, hypo. = hypothesis).

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Experiment	1	3	5	7	9	11	35
<b>Selection of variables</b> (full variable settings for all experiments in supplement 1)							
equal-traders-production-site	yes	yes	yes	yes	yes	Yes	yes
traders-distribution	exp.	exp.	exp.	exp.	exp.	exp.	exp.
network-structure	hypo.	hypo.	hypo.	hypo.	hypo.	hypo.	random
traders-production-site	10	10	10	10	10	10	10
<u>proportion-inter-site-links</u>	<u>0</u>	<u>0.0001</u>	<u>0.0006</u>	<u>0.001</u>	<u>0.002</u>	<u>0.003</u>	<u>(0.001)</u>
maximum-degree	5	5	5	5	5	5	(5)
proportion-intra-site-links	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	(0.001)
proportion-mutual-neighbors	2	2	2	2	2	2	(2)
<b>Edges created in:</b> (example edge counts for seed = 10; other seeds give similar counts)							
Step1	100	100	100	100	100	100	na
Step2	0	50	300	500	999	1499	na
Step3	950	950	937	898	760	529	na
Step4	1204	1151	925	755	394	136	na
Step5	19	19	11	7	2	2	na
TOTAL NUMBER OF EDGES	2273	2270	2273	2260	2255	2266	2272
TOTAL proportion inter-site edges	0.044	0.066	0.176	0.265	0.487	0.706	1
Effects of <i>proportion-inter-site-links</i> and <i>local-knowledge</i>	0.044	0.066	0.176	0.265	0.487	0.706	1

- 4.4 **Network measures** (example measures for seed = 10; other seeds give similar counts)
- The proportion of commercial information available to traders has a limited effect on the wideness of the distribution of products. Experiments where traders have access to the commercial information of 10% of the traders they are connected to show only slightly more widely distributed products than those where traders have access to information from 100% of their contacts (i.e. changing the *local-knowledge* variable between 0.1 and 1; Table 3). A higher integration of markets (i.e. a higher value for *proportion-inter-site-links*) does give rise to more widely distributed products. Despite this wide distribution of products, the range of their distribution (i.e. the difference between the maximum and minimum wideness of four products' distributions per simulation) is rather low. These results suggest that the impact of the *local-knowledge* variable on the wideness of distribution is limited, and that a high degree of market integration as represented by a high value for *proportion-inter-site-links* can give rise to widely distributed products but that it is not sufficient for explaining the differences in the width of products' distributions.

Table 3: Selected variable settings and summary results for experiments designed to evaluate the effects of two independent variables: *proportion-inter-site-links* and *local-knowledge*. The following describes the information presented in Tables 3, 4, 5 and 6. Results are highlighted using a colour range from light grey for 0 and dark grey for 100 (the minimum and maximum widths of distributions in these experiments). 'Ranked width distributions' presents the number of sites each product is deposited on, averaged over 100 iterations per experiment (seed 1-100). Results for the most widely distributed wares in all iterations of an experiment were averaged and reported as 'Product 1', results for the second most widely distributed products as 'product 2', etc. 'Range of distributions' presents summary statistics of the difference in distribution width between product 1 and product 4 for all iterations per experiment. See Supplement 1 for a full list of experiments with their variable settings and summary results.

Experiment	1	2	3	4	5	6	7	8	9	10	11	12
<b>Selection of variables</b>												
local-knowledge	0,1	1	0,1	1	0,1	1	0,1	1	0,1	1	0,1	1
proportion-inter-site-links	0	0	0,0001	0,0001	0,0006	0,0006	0,001	0,001	0,002	0,002	0,003	0,003
<b>Ranked width distributions</b> (number of sites each product is deposited on, ranked from high to low per simulation)												
Average product 1	4,34	4,26	7,25	6,69	22,38	19,1	35,73	29,23	63,09	49,67	79,41	64,61
Average product 2	3,85	3,73	5,67	5,34	18,42	15,69	30,91	24,67	58,73	44,69	75,53	60,81
Average product 3	3,42	3,25	4,55	4,27	15,03	12,31	26,74	21,08	54,29	40,24	72,44	57,52
Average product 4	3,08	3,05	3,67	3,51	11,57	9,12	22,01	16,81	48,41	34,65	68,79	52,45
<b>Range of distributions</b> (maximum number of sites minus minimum per simulation)												
Average	1,26	1,21	3,58	3,18	10,81	9,98	13,72	12,42	14,68	15,02	10,62	12,16
Median	1	1	3	3	11	10	13	11,5	14	14	10	11,5
Mode	1	1	4	3	12	9	12	11	12	13	8	12
Standard deviation	0,63	0,70	1,56	1,40	4,48	4,13	5,63	5,55	6,63	6,96	4,80	5,78
Minimum	0	0	1	0	2	2	4	3	2	2	1	1
Maximum	3	3	8	8	23	20	37	28	33	40	26	35

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Effects of *traders-production-site* and *max-demand*

- 4.5 The results of experiments 13 to 20 presented in Table 4 show the distribution of products in scenarios where an equal number of traders are present on each of the four production sites, determined by the variable *traders-production-site*, and the rest of the traders are distributed exponentially among the remaining sites, determined by the variable *traders-distribution*. Increasing either or both the *traders-production-site* and *max-demand* variables results in more widely distributed products (i.e. higher width of distributions for products 1, 2, 3, and 4), but does not lead to very strong differences between the width of products' distributions (i.e. limited ranges of distributions).

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Table 4: Selected variable settings and summary results for experiments designed to evaluate the effects of two independent variables: *traders-production-site* and *max-demand*. See caption Table 3 for a detailed description of the information presented in this table.

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Experiment	13	14	15	16	17	18	19	20
Selection of variables								
traders-production-site	1	1	20	30	10	10	10	30
max-demand	1	10	10	10	1	20	30	30
proportion-inter-site-links	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
(number of sites each product is deposited on, ranked from high to low per simulation)								
Ranked width distributions								
Average product 1	3.94	16.16	61.23	73.02	14.45	43.53	48.21	80.06
Average product 2	3.14	13.74	55.84	68.6	12.45	37.96	42.11	75.65
Average product 3	2.6	11.64	51.95	64.93	10.82	32.83	36.28	72.2
Average product 4	2.11	9.33	45.77	59.56	9.12	27.1	30.26	66.51
Range of distributions (maximum number of sites minus minimum per simulation)								
Average	1.83	6.83	15.46	13.46	5.33	16.43	17.95	13.55
Median	2	7	14	13	5	15	18	12
Mode	2	6	14	14	5	13	24	11
St.Dev	0.84	2.92	8.56	6.77	2.34	7.02	7.60	6.39
Minimum	0	2	3	2	1	2	2	2
Maximum	4	16	44	35	13	43	42	31

Effects of *traders-distribution* and *equal-traders-production-site*

- 4.6 The results of the experiments presented in Table 5 are the outputs of scenarios where the number of traders at the four production sites are unequal and follow the exponential or uniform (determined by the variable *traders-distribution*) distribution of all traders among all sites. We notice that an overall exponential distribution of traders on all sites in a scenario with limited market integration does not give rise to widely distributed products and high ranges of distribution (see experiment 21). However, increasing the degree of market integration (by increasing the *proportion-inter-site-links* variable) does result in more widely distributed products and higher ranges of distribution (see experiments 24-28). Moreover, when one production site has far more traders than any of the others, the product produced at this site will be far more widely distributed than the others (see experiment 33). We again notice that, even with an unequal number of traders at production sites, a *local-knowledge* value of 0.5 results in slightly more widely distributed products and slightly higher ranges of distribution than a value of 1, as mentioned in section 'Effects of *proportion-inter-site-links* and *local-knowledge*' above (compare experiments 24 and 31). A uniform distribution of all traders among all sites results in wide distributions of products, but also a low range of distribution (see experiment 23).

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Table 5: . Selected variable settings and summary results for experiments designed to evaluate the effects of two independent variables: *equal-traders-production-site* and *traders-distribution*. The setting for *traders-production-site* for experiment 33 is given in brackets, because in each iteration of this experiment the number of traders at production sites A, B, C, and D was set to 30, 1, 1, and 1 respectively. See caption Table 3 for a detailed description of the information

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presented in this table.

Experiment	21	23	24	25	26	27	28	31	33
<b>Selection of variables</b>									
equal-traders-production-site	false	false	false	false	false	false	false	false	false
traders-distribution	exp.	uniform	exp.	exp.	exp.	exp.	exp.	exp.	exp.
proportion-inter-site-links	0.0001	0.001	0.001	0.001	0.002	0.002	0.003	0.001	0.001
traders-production-site	na	na	Na	na	na	na	na	na	(30,1,1,1)
maximum-demand	10	10	10	30	10	30	10	10	10
local-knowledge	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1	0.5
(number of sites each product is deposited on, ranked from high to low per simulation)									
<b>Ranked width distributions</b>									
Average product 1	9.55	48.45	51.36	54.94	56.87	82.01	87.09	35.72	62.43
Average product 2	6.91	42.17	35.31	39.55	41.45	70.42	75.71	22.34	16.23
Average product 3	5.4	37.18	25.7	28.79	30.2	57.8	62.76	15.61	13.48
Average product 4	4.18	30.04	16.44	18.63	19.28	42.86	47.25	9.84	10.38
<b>Range of distributions</b> (maximum number of sites minus minimum per simulation)									
Average	5.37	18.41	34.92	36.31	37.59	39.15	39.84	25.88	52.05
Median	5	17.5	34	37	37	39.5	40	24.5	52
Mode	3	16	26	32	32	48	42	21	55
St.Dev	3.17	7.32	11.28	12.04	14.23	14.93	17.44	10.18	7.57
Minimum	1	3	8	5	8	6	6	6	37
Maximum	17	35	73	68	70	74	78	53	75

#### Comparison with randomly created networks

- 4.7 Table 6 presents results of experiments with the hypothesised social network structure (experiments 22; 24; 25; 33) and experiments with the same independent variable settings but with a randomly created network structure with the same density (experiments 35; 29; 32; 34). The experiments with randomly created networks give rise to more widely distributed products in all tested cases. This is not surprising since the proportion of all links that exist between pairs of traders on different sites is much higher in experiments with randomly created networks than in those with the hypothesised social network structure (Table 2). However, the experiments with randomly created networks do not give rise to high ranges of distribution (Table 6). See in particular the average ranges of experiments 35 and 32, which are much lower than those of experiments with the hypothesised social network structure (experiments 22 and 25 respectively). However, experiment 29 (randomly created network) shows a very similar average range to that of experiment 24 (hypothesised network structure). As illustrated in Figure 6, this is caused by the very strong differences between iterations of the experiment in the distribution of wares, and of the least distributed ware in particular (ware 4 of experiment 29 in Fig. 6). Finally, in experiment 33, strong differences in the number of traders at each production site gave rise to one very widely distributed product and three less widely distributed products. Note that this reflects the archaeologically attested pattern described in section Explaining pottery distributions that we aim to study here. The results of experiment 34 with a randomly created network and otherwise the same variable settings as the latter experiment echo these results, but show a higher range and wider average distribution for all four products, as would be expected given the randomly created network (Table 6; Fig. 7). This result suggests that the hypothesised network structure is less important for giving rise to widely distributed products and strong differences between distributions in scenarios where one production centre produces a far higher quantity of products than the other three.

Table 6: Selected variable settings and summary results for experiments designed to evaluate the effects of one independent variable: *network-structure*. The setting for *traders-production-site* for experiments 33 and 34 is given in brackets, because in each iteration of these experiments the number of traders at production sites A, B, C, and D was set to 30, 1, 1, and 1 respectively. See caption Table 3 for a detailed description of the information presented in this table. Note how the experiments with a randomly generated network structure have a higher width of distribution, but not necessarily a higher average range of distribution (with the exception of experiment 34).

Experiment	22	35	24	29	25	32	33	34
<b>Selection of variables</b>								
network-structure	hypo.	random	hypo.	random	hypo.	random	hypo.	random
equal-traders-production-site	true	true	false	false	false	false	false	false
traders-distribution	exp.	exp.	exp.	exp.	exp.	exp.	exp.	exp.
proportion-inter-site-links	0.001	na	0.001	na	0.001	na	0.001	na
traders-production-site	10	10	na	na	na	na	(30,1,1,1)	(30,1,1,1)
maximum-demand	10	10	10	10	30	30	10	10
<b>Ranked width distributions</b> (number of sites each product is deposited on, ranked from high to low per simulation)								
Average product 1	44.33	91.28	51.36	91.31	54.94	97.41	62.43	95.3
Average product 2	38.23	89.58	35.31	83.26	39.55	94.19	16.23	39.62
Average product 3	33.13	88.01	25.7	73.44	28.79	89.47	13.48	35.7
Average product 4	27.6	86.4	16.44	58.26	18.63	79.32	10.38	30.83
<b>Range of distributions</b> (maximum number of sites minus minimum per simulation)								
Average	16.73	4.88	34.92	33.05	36.31	18.09	52.05	64.47
Median	16.5	5	34	30.5	37	14	52	64
Mode	19	4	26	11	32	3	55	62
St.Dev	6.84522	2.10371	11.2833	16.0684	17.0422	15.2244	7.57017	5.49082
Minimum	0	0	0	0	0	0	37	56
Maximum	36	36	36	36	36	76	75	91

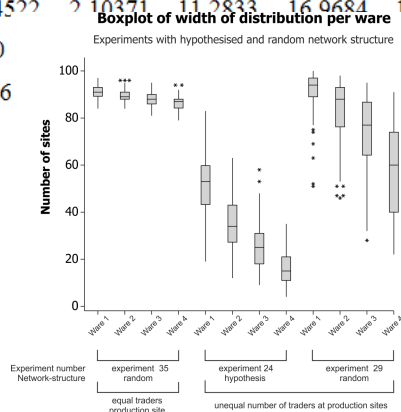


Figure 6. Boxplot of the width of distribution per ware for four experiments. Each boxplot combines the results of 100 iterations per experiment, and they represent the wares from the most widely distributed (ware 1) to the least widely distributed (ware 4). Note that the results of experiment 35 show widely distributed wares but with a very limited range of distributions between different types of wares. Experiments 24 and 29 have the same independent variable settings but for their hypothesised and randomly created network structures respectively. Their average ranges are similar but experiment 29 shows more widely distributed wares. See Table 6 for summary statistics and Supplement 1 for all independent variable settings for the experiments presented here.

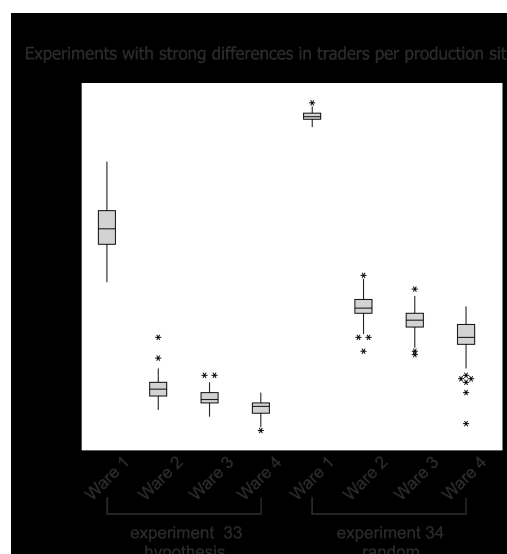


Figure 7. Boxplot of the width of distribution per ware for two experiments. Each boxplot combines the results of 100 iterations per experiment, and they represent the wares from the most widely distributed (ware 1) to the least widely distributed (ware 4). Experiments 33 and 34 have the same independent variable settings but for their hypothesised and randomly created network



structures respectively. Note the similar range of distribution of both, and the similar pattern of one ware being far more widely distributed than the other three, but wares are more widely distributed on a randomly created network. See Table 6 for summary statistics and see Supplement 1 for all independent variable settings for the experiments presented here.

## Discussion and conclusions

- 5.1 In this paper we have presented the conceptualisation and implementation of MERCURY, an Agent-based Model of Roman Trade, as well as the results of a series of experiments. This work represents the first attempts at formalising and simulating some of the hypotheses that aim to explain Roman tableware distributions using computational modelling (see Graham and Weingart (2015) for related work). To further clarify the potential of this approach, we will discuss the implications of the results, how they suggest some promising future research directions and ways of modifying and improving MERCURY to answer a wider range of research questions.
- 5.2 The main results are represented in Figure 8 and indicate that the *proportion-inter-site-links*, *traders-production-site*, and *max-demand* variables positively correlate with the width of distribution of all the products but not with the range of distribution (i.e. not with strong differences in the distributions between products similar to the ones observed in archaeological data). Secondly, randomly created networks, which have a higher proportion of inter-site links than the hypothesised social network structure, also give rise to a wide distribution of all products but not to high ranges of distribution (i.e. they show a small difference between the most widely and least widely distributed products). The pattern of a strong difference between the most widely and least widely distributed products is achieved only in a scenario in which one production site has far more traders and therefore has the potential of exporting more produce than any of the others (see experiment 33). This result holds true even when the hypothesised social network structure is replaced by a randomly generated network (see experiment 34).

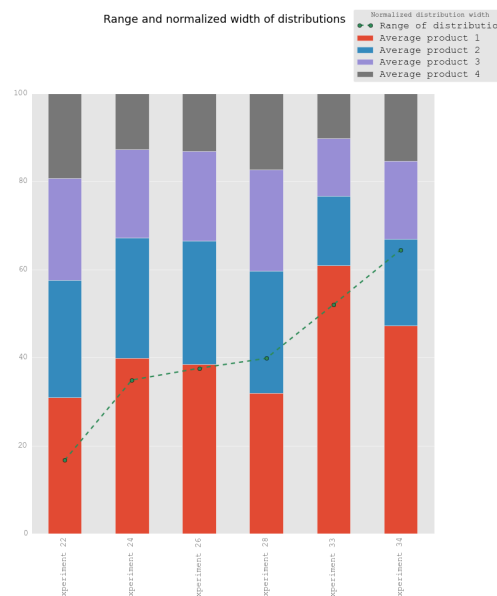


Figure 8. Range and normalized width of distribution for selected experiments. The pattern observed in the archaeological data (i.e. that one product is significantly more widely distributed and the difference in distribution width between this product and the least widely distributed product (range) is high, see Fig. 1) was only reproduced in scenarios where one production centre has far more traders than any other production centre and the number of inter-site links is high (*proportion-inter-site-links* 0.001) (see experiments 33 and 34). This pattern is not strongly affected by the proportion of available commercial information (*local-knowledge*).

- 5.3 The results presented here suggest that market integration in part might cause wide distributions of tablewares and differences in tableware distributions. However, market integration alone is not sufficient as an explanation. The potential of one production centre to produce far more than the others is a second necessary ingredient. Nevertheless, limited degrees of market integration are unlikely to result in wide tableware distributions and strong differences between the tableware distributions. We therefore argue that the emphasis on limited market integration in Bang's model is highly unlikely.
- 5.4 The aim of this research was not to find an exact fit to the archaeologically observed data patterns, but to investigate elements of two conceptual models and produce predictions for each of them which can then be compared to broad archaeologically attested patterns. We have shown that some of the causal factors of the proposed conceptual models (e.g. changing the availability of commercial information from trade contacts) turn out to have less of an impact on generating the pattern of interest, while other factors show more promise in this regard (e.g. changing the degree of market integration). Under the conditions and assumptions imposed in this particular implementation of Bang's and Temin's conceptual models, our experiments suggest that future research into the functioning of tableware distribution processes should focus more on two factors: (1) actors and processes that enable market integration, and (2) the requirements to enable extremely high production of tableware consistently throughout long time periods. The former should include a closer look at the role of government and institutions in regulating trade and in providing incentives to individuals or groups of traders to supply for large demands, as well as into those commercial actors



(individuals, communities, institutions) that had the financial and logistical means to gather reliable commercial information and trade between markets. The latter should include an examination of the possibility that historical contingency played a role in giving an edge to one type of tableware production centre over others, for example one tableware (ESA) being produced first and using the earlier development of distribution channels as an advantage to remain the dominant tableware in the Eastern Mediterranean. Moreover, it should be evaluated whether other factors hinted at in this model might have contributed to one tableware being more widely distributed, such as the existence of an urban hub close by the tableware production centre or region, which acts as a primary and stable source of demand for the product, and a productive hinterland able to supply the primary products and labour needed to supply for high demands.

- 5.5 Moreover, the model could be improved by adding a market-clearing mechanism, a set or variable cost of transporting goods, and a more controlled conceptualisation of time. Finally, the model can be expanded to test some of the topics of future research interest suggested above by elaborating on the production processes, allowing for heterogeneous traders with different rules of behaviour (which would leverage more the advantages of ABM than the current version of the model), allowing for changes in the social network structure, incorporating state influence, distinguishing between channels for the flow of information and those for the flow of goods, and considering transport costs. Some of these might require alternative conceptualisations to the one presented here.
- 5.6 We have placed a particular emphasis here on illustrating that two conceptual models which stand for fundamentally different interpretations of the functioning of the Roman economy can be compared by abstracting them using the same set of concepts. Indeed, we argue that the conceptualisation is the most crucial stage of any computational modelling of the Roman economy and that it should be considered a task of the archaeologists and historians who create conceptual models. It should be clear that we do not argue that every scholar of the Roman economy should become a computer programmer. Instead, we believe that in order for the discussion on the functioning of the Roman economy to progress, scholars should (a) clearly define the concepts used and discuss exactly how these differ from the concepts used by others, (b) make explicit how these concepts can be represented as data, (c) describe the expected behaviour of the system using the defined concepts, (d) describe the expected data patterns resulting from this behaviour, and (e) define how (if at all) archaeological and historical sources can be used as reflections or proxies of these expected data patterns. By doing so, conceptual models of the Roman economy, as they are envisaged by their authors, hold the potential of being compared and falsified if the necessary archaeological or historical sources become available. These conclusions also do not imply the limitation of the study of the Roman economy to a single conceptual framework or a limited set of computational models. At this early stage of the use of computational modelling in Roman economy studies, multi-vocality of concepts and computational models is a virtue. What matters is to define how these differ and to develop them in ways that allow for comparisons between them.
- 5.7 The study of the Roman economy is a fascinating and thriving discipline in need of methodological developments. We have shown here that agent-based modelling shows great potential in this respect, and argue that the use of computational modelling as a whole should become more common practice in the study of the Roman economy.

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## Notes

<sup>1</sup><https://github.com/NetLogo/NetLogo/wiki/Extensions> (accessed 05-01-2015).

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