# MODELLING CULTURAL DYNAMICS: A MACROSCOPIC APPROACH TO CULTURAL TRANSMISSION IN THE PREHISTORIC AEGEAN[*]

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## INTRODUCTION

In this paper we pursue a novel transdisciplinary approach to the question of cultural dynamics, focussing particularly on the transmission of cultural traits across socio-physical space. In order to think through some of the themes involved we take as a case study an inter-regional phenomenon known as ‘Minoanisation’ (Wiener 1990; Broodbank 2004). This term describes a set of processes observed in the prehistoric Aegean (specifically the Middle and early Late Bronze Age) whereby ‘Minoan’ cultural traits find themselves transmitted beyond the Minoan sphere, i.e. the island of Crete. That is to say, communities in regions such as the Cyclades, the Dodecanese, coastal Asia Minor and the Greek mainland adopt aspects of Cretan culture, both in the form of actual imports from Crete and also local imitations thereof. These cultural elements include pottery shapes and styles, stone vases, loomweights and wall paintings; not only new forms of material culture, but also, presumably, new cultural practices.

There are many aspects of Minoanisation that archaeologists are keen to understand. Why do these various communities decide to adopt Minoan cultural traits in this way and at this time? Given Crete’s possible economic and political pre-eminence in the southern Aegean, to what extent are they able to choose at all? Why do we see different patterns of adoption in different areas? To what degree is Minoanisation facilitated by increased political centralisation on Crete itself, with Knossos perhaps the island’s primary centre (Knappett and Nikolakopoulou in press)? And what was in it for Knossos and Crete anyway? These and other questions are essentially concerned with the how and why of cultural transmission. In terms of ‘how’, we might ask, ‘what are the mechanisms that allow for cultural traits to be transmitted and reproduced ‘faithfully’ across such wide socio-spatial areas’? This question needs to take into consideration both the potential receptiveness of communities to new cultural traits, and also the inherent attractiveness or ‘stickiness’ of those cultural traits. This is the level at which the ‘memetic’, Darwinian approach to cultural transmission is pitched: one looks at both the ‘virulence’ of the meme and the ‘susceptibility’ of the population through which it might or might not spread (Shennan 2002; Bentley and Shennan 2003; Bentley et al. 2004; Mesoudi et al. 2006). When it comes to the ‘why’ question, however, this kind of approach merely states that the meme seeks to sustain and propagate itself. There is no more directedness than this.

We propose instead an approach that can give more satisfactory answers, we believe, to both ‘how’ and ‘why’ questions. The way in which we achieve this is by taking a different scale of analysis: the macroscopic rather than the microscopic. Our approach looks at the overall structure of the network of interactions, arguing that sites are ‘enacted’ by their network position. This is a relational approach that can traverse different scales, and can actually be applied at the micro-scale too. By the same token, we also argue that cultural traits are enacted by their wider networks of association. So the ‘how’ of

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cultural transmission, we argue, is at least in part explicable through the macro-scale of network dynamics. In other words, the variable spread of Minoan traits across the southern Aegean may have something to do at the micro-level with individual choice, or with the particular features of the trait in question; but it also hinges significantly around the position of that trait and that community within the wider network. Moreover, our macroscopic approach also permits us to address the 'why' of cultural transmission more satisfactorily than do memetic approaches; we accept that cultural transmission can be a directed process at the inter-regional level, aimed at increasing 'functionality' in a way that goes beyond 'fitness'. In the case of Minoanisation, this could be viewed as a directed process of cultural affiliation aimed at improving the reliability of information concerning scarce resources, notably metals (which would have been crucial to elites on Crete, although Crete has no metal resources). Another facet unanticipated in memetic approaches is that the organisation, let us say the network of sites connected together by Minoan-ness, can itself undergo further unexpected transformation. The network established with one functionality in mind may actually allow new ways of thinking from which new organisational possibilities might ensue. This 'ratcheting' effect means that the organisation can transform itself, a socio-cultural process which finds no easy equivalent in the 'population thinking' that underlies biological evolution (Lane et al. forthcoming).

Thus what we present is a way of modelling cultural transmission that is macroscopic and which does not find the 'meme' to be a useful unit of analysis. We do not wish to move entirely away from biological approaches, as there are surely elements of cultural transmission which can be understood in terms of 'random drift'. Indeed, in the network models we present there are aspects which are, to some degree, 'random'. However, what we envisage is an approach to cultural dynamics that does not simply reduce the cultural to the biological, finding instead a pathway that can mediate between directed and undirected facets of cultural transmission. The way in which we move to achieve this through a macroscopic approach is now outlined. This builds on earlier work by some of us (Evans, 2006, 2007) to establish proof of principle for this approach.

## MODELLING THE MACROSCOPIC: THE 'ENERGY LANDSCAPE'

Our aim is to develop forms of network analysis that can model the behaviour of 'organisations' at the macro-level (with a view to shedding light on cultural dynamics across socio-physical space). In the field of social network analysis, models do exist which are using graph theory in increasingly complex ways (De Nooy et al. 2005; Carrington et al. 2005). However, we have decided to go a step further and combine some of these insights with techniques from statistical physics. Statistical physics shows how large numbers of interacting entities often have relatively simple generic behaviour on large scales regardless of the details of their interactions. Network theory shows how specific behaviour is embedded within this. Our Bronze Age Aegean network consists of a set of vertices, or sites, correlated to centres of population/resources, and their links. The links, or edges, which are directional, are summarised as representing 'trade', an imprecise term for all kinds of interaction (markets, redistribution, exogamy, etc) and, more specifically for this paper, **cultural transmission**.

While we wish to stay within the humanistic approach of some previous approaches to regional interactions in the Aegean, such as that of Broodbank (2000), examples from hard science can be illuminating in that they suggest twin approaches to statistical behaviour, those of 'statistical mechanics' and 'thermodynamics'. The former shows how the system as a whole behaves as an aggregate of the dynamics of the individual constituents. In the language of social network models, this would correspond to an agent-based approach. However, a thermodynamical approach shows how, from general principles, we can extract the same global ‘equation of state’, without having to look at a microscopic level. This is the approach that we adopt here (and is another way of saying that we do not need to identify a microscopic unit of cultural transmission, such as the meme).

The method is straightforward, in principle. We propose a ‘utility’ function or, in contemporary economic parlance, a ‘cost/benefit’ function $H$ for the network that, in some sense, represents the ‘energy’ required to maintain it. Most simply, we associate a single output $v_i$ to each site $i$, which we can interpret as its detrended population or occupation index (i.e. the fraction of its total resources that have been exploited). Similarly, we associate a directional edge variable $e_{ij}$ to each link between sites $i$ and $j$, representing the fraction of the interaction *from* site *i to* site j (and which need not equal $e_{ji}$). The sum of the *outgoing* $e_{ij}$ over $j$ for each $i$ is therefore unity. By attributing an agency of some sort to the system (‘rational choice’), a system with low energy $H$ is close to some optimal solution in which all the different constraints and interactions are balanced. For instance, overpopulation or overuse of resources carries a ‘cost’ and links (interactions such as trade, intermarriage etc.) bring benefits, but at a price.

As discussed elsewhere (Evans et al. 2006; 2007), we separate $H$ into four terms:

$$H = -\kappa S - \lambda E + (j P + \mu T). \qquad (1)$$

The individual terms are understood as follows:

i) Each site $i$ is given a physical location and a fixed carrying capacity $S_i$ (its effective size). $S$ is a sum of terms, one term for each site, which describes the benefits accruing from the site as a function of the fraction $v_i$ of its total resources that have been exploited. We might say that the active population at a site is $S_i v_i$. Over-exploitation is undesirable while under-exploitation is a wasted opportunity. By itself, $v_i$ takes a minimum at some intermediate value. Initially, we assume that all sites are equally easy (or difficult) to exploit and all $S_i$ are equal.

ii) $E$ is the exchange term which shows the benefits of inter-site exchange (trade, influence) in a way that depends on both the properties of the sites and the network and weight of their interactions. As such, it is a sum of terms, one term for every pair of sites that is linked by exchange in the sense above. We also define an effective distance $d_{ij}$ *from* site *i to* site *j*, measured in units of $D$, the distance scale for inter-site travel. The parameter λ determines the importance of inter-site interaction.

iii) The final terms (in brackets) enable us to impose constraints on population size ($P$), total trading links (and/or journeys made) in $T$. Increasing $j$ corresponds to reducing regional population (and increasing $\mu$ reduces interactions).

To be concrete, we think of the ‘energy landscape’ described by $H$ statistically, adopting a Boltzmann-Gibbs distribution, whereby the likelihood of achieving a particular value of $H$ is

$$H = -T \log[\text{likelihood}]. \qquad (2)$$

The assumption is that the system will evolve from the unlikely ‘peaks’ to the more likely ‘valley bottoms’. The ‘temperature’ *T* is a measure of ‘volatility’, a measure of the ease for taking one path through the landscape, rather than a nearby path in moving downhill. The parameters that control the contours of the landscape are measures of site independence or self-sufficiency, and constraints on population size, etc. Thus, for example, as populations grow or total trade volume increases, the landscape changes, and the positions of the valleys into which the system wishes to fall change. The implementation is by a Monte Carlo algorithm in which volatility is progressively reduced until sequential updates are essentially the same.

**Gravity vs. Asymmetric Models**

There is ambiguity in how to construct the components of *H.* Whereas the nature of S is relatively straightforward (over- and under-use of resources is penalised), there are three main variations in the choice of *E*; we can choose between ‘gravity’ and two ‘asymmetric’ models. Essentially, the gravity model takes a group of small sites with clustered links and considers it as one large site with a single large link, in the same way that the gravitational force of several masses acts as a single point at a distance. The benefit of the link is proportional to the product of the two larger sites’ sizes. This model has the advantage of robustness: the ‘coarse graining’ of the model means that, to a first approximation, we do not need to know individual site details, just the aggregate population/resources of an island. This is important as there is a patchy archaeological record: if a new site is discovered on an island this is relatively unimportant, as the calculations are based on island-wide output.

In comparison, asymmetric models only consider the site size at one end of the link in determining its strength. In contemporary economic terms a ‘supply side’ model only considers the size of sites to which a link is made. This means that even a small site can gain a benefit by linking to a large site, but will not get additional strength by growing itself. A ‘demand side’ model site gains more benefit from links by having a large local population, regardless of the supply site sizes. Unlike the gravity model (both ‘supply *and* demand’), these models are sensitive to island site details: if, say, one splits a large site in two, this would produce a different system to the gravity model which aggregates local site sizes, and thus are not robust. We shall consider all possibilities below.

The gravitational model that we have proposed that embodies the above is

$$H = -\kappa \sum_{i} S_i v_i (1 - v_i) - \lambda \sum_{i,j} V(d_{ij} \big/ D).(S_i v_i).e_{ij}.(S_j v_j)$$

$$+\ j \sum_{i} S_i v_i + \mu \sum_{i,j} S_i v_i e_{ij}, \qquad 0 \le \sum_{j} e_{ij} \le 1, \quad v \le v_{\max}.$$

The sums are over the different sites or over all pairs of sites, labelled by *i* or *j*. Asymmetric ‘supply’ or ‘demand’ models are obtained by setting the first factor $v_i$ or the second factor $v_j$ to unity in the second term. The ‘potential’ coefficient $V(x)$ is chosen to be unity for $x < 1$, very small for $x > 1$.

In our simulations we have restricted ourselves to the 34 sites listed below, covering major islands, the city states of Crete and important mainland centres. More can be included, but these are enough to display the main features of our approach.

Table 1: Key to sites used in the Monte Carlo simulations

| | | |
|---|---|---|
| 1. Knossos | 12. Kastri | 23. Paroikia |
| 2. Malia | 13. Naxos | 24. Amorgos |
| 3. Phaistos | 14. Kea | 25. Ios |
| 4. Kommos | 15. Karpathos | 26. Aegina |
| 5. Ayia Triadha | 16. Rhodes | 27. Mycenae |
| 6. Palaikastro | 17. Kos | 28. Ayios Stephanos |
| 7. Zakros | 18. Miletus | 29. Lavrion |
| 8. Gournia | 19. Iasos | 30. Kasos |
| 9. Chania | 20. Samos | 31. Kalymnos |
| 10. Akrotiri | 21. Petras | 32. Myndus |
| 11. Phylakopi | 22. Rethymnon | 33. Cesme |
| | | 34. Akbuk |

## WHAT MAKES A GOOD MODEL?

What makes a good model is difficult to quantify, but from our previous discussion we need to consider the following in our interpretation of the data,:

1) What is the extent of output variation between program runs?

The approach outlined above looks excessively prescriptive, in purportedly identifying a unique network configuration for each input. This is not so. Given that a network with $N$ vertices has $N^2$ parameters, the 34 sites under consideration lead to $H[v_i ,e_{ij}]$ describing an ‘energy landscape’ with 1000 dimensions. There could be many comparable (essentially equally desirable) low-energy states of the network accessible by the Monte-Carlo method. If very different network configurations are equally efficient, this suggests that the island system is inherently dynamic.

2) What is the extent of output variation between input parameter changes?

Changing input parameters may result in unexpectedly large changes in outcome. That is, a small parameter change can knock the system into one of a few other, stable configurations. An excessively sensitive output may undermine the programme's claim to describing a physical model; on the other hand, it might be hard to dismiss such behaviour as non-physical when such phenomena as population collapse can and do happen in the MBA. In fact, analytic solutions to simplified network models show how this kind of behaviour can arise. Gravity models, due to the mathematical consequences of $H$ acquiring negative eigenvalues, permit runaway site growth or population collapse with only minor $\lambda$ variations. On the other hand, asymmetric models are much less likely to show such dramatic behaviour because links between large sites are costly to establish and less beneficial than in the gravity model; consequently there is less for them to lose.

3) What is the extent of output variation between different models?

Changing the underlying assumptions of how sites interact may result in large qualitative and quantitative differences between outputs. The question then becomes, which model is appropriate? Similarities would suggest that the physical input data (site locations) retains a high importance, which is as it should be. Large differences would suggest that the model apparatus perhaps plays an excessively large role. One would, *a priori,* feel that the gravity model is generally preferable, because it minimises the impact of our ignorance of site details. However, of itself this is no guarantee of correctness, and such coarse-graining is more a reflection of the nature of meso-level interactions within the macroscopic network. While a strong case can be made for this to be sensible in the MBA, the work of Broodbank (2000) suggests that it is totally inappropriate for the EBA Cyclades, in which interactions are determined by short-range rowing boats, prior to the use of sail.

All these points considered, if one observes some similar, salient qualitative characteristics between runs, parameters and models, it would suggest an underlying robustness to the overall approach: that our model captures something essential to the Aegean system. Thus far little extended work has been done to probe the emergent differences between the different models and this paper represents a first step in this direction.

## MOVING TOWARDS THE ARCHAEOLOGICAL RECORD

As we have already said, there are two types of input in our model once we have made a choice between gravitational and non-gravitational exchange. The first are essentially geographical; the choice and separation of sites and their carrying capacities, the distance scale $D$. [Less importantly, there is a short-distance scale $d$ (say *5km*) in the definition of $V(x)$ that sets the maximum separation for which two sites can be aggregated as one.] The other parameters are a reflection of global network properties; the inter-site interaction scale $\lambda$ and the constraints on total population and trade.

### Weight, Strength and Rank*:*

Our model output is also of two types. The first is the relative exploitation of resources $v_i$ or, equivalently, site populations, which we term 'site weight'. The second is the strength $e_{ij}$ of inter-site links. The strength of a *site* can be understood as the sum of the *incoming* $e_{ij}$ at the site.

The $e_{ij}$ need to be processed in order to get useful information that can be compared to the archaeological record. We can do this in several ways that permit a dynamical interpretation, by introducing agents indirectly. Suppose we want to understand which sites are dominant, be it in a cultural or political sense. Imagine a random walker who moves from site to site. At each time step the walker must choose an edge to follow in proportion to the weight of the edge, $(S_i v_i e_{ij})$ if moving from site i to site j. This is a Markov process where the probability of being at a site i at time t is given by $r_i(t)$ and the vector $r(t)$ evolves as $r(t) = (\Pi)^t r(0)$. Here $\Pi$ is the transition matrix where $\Pi_{ij} = S_j v_j e_{ji}$. If a dead end is reached, the walker starts again from a random vertex chosen with probability proportional to the weight $(S_i v_i)$ of the vertex. We can then rank sites according to the frequency with which they are visited. This is a global attribute, in which a high-ranking site is more important to the network than a low-ranking one. An example of the result is shown in Figure 1. This clearly identifies which sites are truly peripheral, such as Paroikia in the Cyclades which is not close to the route between Crete and the Dodecanese. It also shows a hierarchy of Crete, the Dodecanese and then the Cyclades. Note that this also illustrates how one can emphasise the relational aspects over the physical locations as we use a non-geographical layout in Figure 1 (the Kamada-Kawai scheme as implemented in `pajek`, see references for details).

However, of itself ranking does not determine the zones of influence of highly-ranked sites directly as, for example, the Renfrew tent model (see Cherry 1987 for a discussion) attempts. To do this we again exploit a random walker to access the global shape of the network, starting from site i, but with the proviso that, after each walk, we restart the walk from site i with probability $p$. The average walk length is then $([1-p]/p)$. The frequencies of visits to a site j when scaled by the weight of starting site i, $(S_i v_i)$, gives us a measure of the *influence* of site i on any other site j. This is an influence matrix which can be used as the basis of block modelling (for example see De Nooy et al. 2005 for details). Here let us just associate each site to the site that has the largest influence over it. An example is shown in Figure 2 which indicates that for short ranges, ($p = 0.5$), only Eastern and Western Crete form large regions dominated by Knossos and Gournia. Note that Malia remains independent suggesting that the link to the Cyclades via Thera is crucial in this model to its size and hence to its ability to remain independent of the influences of others. It is no coincidence that the next biggest group is in the Cyclades including Thera. As we increase the range nothing happens until at about $p = 0.6$, when there is a dramatic shift to three groups: Ios dominates the Cyclades, Miletus dominates the Dodecanese, and Gournia dominates Crete and all other outlying sites including Rhodes. A number of interpretations are possible; one is that this represents zones of weaker influence or alternatively this would be the pattern if sites had the power to exert their influence further.

## Gateway sites

The latter example above was chosen to demonstrate the method, and not because of its agreement with archaeological data. As yet, it is premature to try to correlate an influence matrix to actual cultural transmission (e.g. the spread of the potter's wheel) witnessed in the archaeological evidence until we have understood the implications of simple ranking better. That is the more modest goal of this paper.

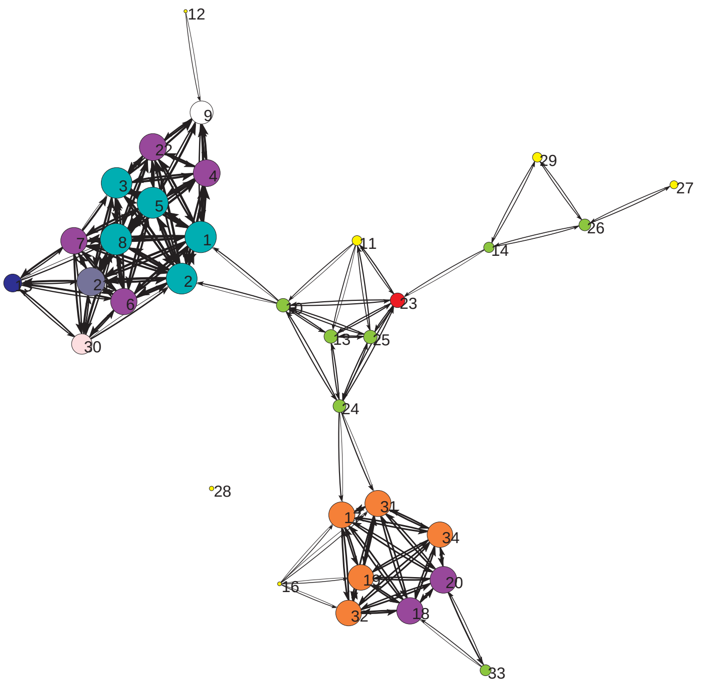


**Figure 1: Monte Carlo analysis for $\kappa=2.0$, $\lambda=1.0$, $\mu=0.35$ and $j=0.7$. Sites are ranked using the diffusion model, the size of the vertex proportional to ranking. Central Cretan sites are ranked most highly. Sites are labelled by their numbers given in Table 1. In this figure we use the Kamada-Kawai visualisation method which responds to the topological structure of the network.**

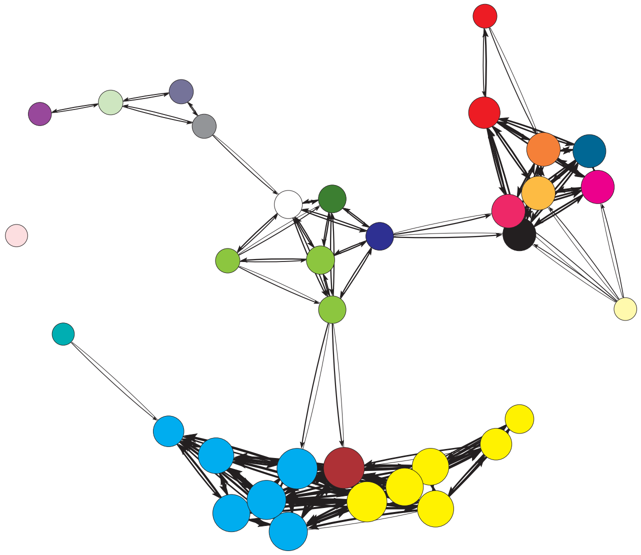


**Figure 2: The pattern of dominance for $p=0.5$ . for the parameter values of Fig. 1. Note that Crete splits into a Western and Eastern region dominated by Knossos and Gournia respectively. Only Malia is strong enough to remain independent. The vertex size is proportional to the vertex weight; the largest sites are three times as big as the smallest.**

Figure 1 is suggestive, but too qualitative to identify key features for which there may be support. When one plots relative site weight against relative rank, one generally sees a positive, linear relationship between these quantities. A negative deviation from the linear trendline fit (least-squares method) suggests that, for the site's weight, it has less interaction with the network than one would expect. This could be due to it being overshadowed by more important sites. Conversely, a large positive deviation suggests that a site plays an important role in the network. We term such outlier sites 'gateway' sites. The geographical layout of the network is such that there is a clustering of sites into groups: the Cretan sites in the south, the Dodecanese in the east, and the central and western Cyclades. Therefore, by way of physical explanation for such importance, it may be that such outlier sites play an important role as a 'gateway' to other regional clusters. This makes sense in that, if one is travelling by sail and as such has a limited range, it would be inevitable to plan the route using the nearest available waypoint. An example of such a site is Rhodes (fig. 1), which geographically lies between Crete and the Dodecanese. To sound a note of caution, however, it may be that some regional clusters predominate at lower levels of λ, with the clusters suggested by the physical input only fully emerging at higher λ levels. Therefore, in the case of low λ levels the notion of 'gateways' could be inappropriate.

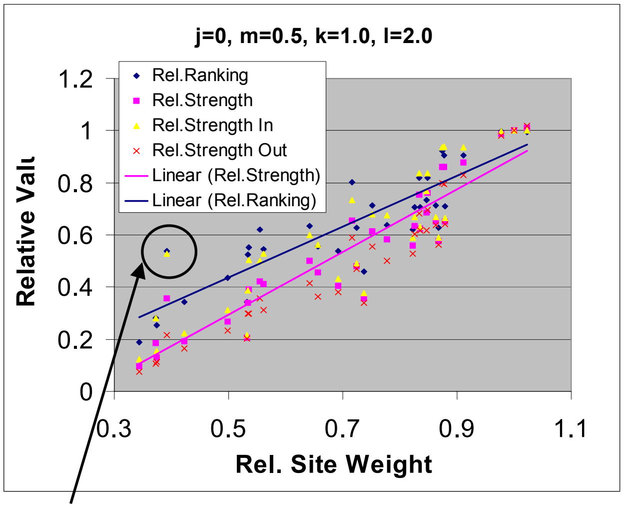


Fig 3. Outlier site (Rhodes)

This greater importance for such gateway sites ought, one would imagine, be clear in the ranking distribution. A random walker would visit such gateway sites more often, as it would have to pass through them to get from one region to another. On the other hand, if interaction levels are low some of the gateway sites may have weak links to other regions, or no links to them at all.

## RESULTS

In lieu of physical data to calibrate system parameters (notwithstanding the fact that we lack a clear physical meaning for each of them anyway), we can only discern causal patterns for the parameters by making comparisons between networks generated under the variation of one parameter whilst the others remain fixed. This reveals the influence each individual parameter has on the overall system. However, in a multidimensional system such as this it is harder to know how the effects of each parameter might change as the others change also. Therefore, any conclusions as to the role of a parameter, or the differing behaviours of each model, must be necessarily limited to the range of investigation undertaken. Broader assertions must be more tentative. Once a comfortable 'working range' has been established for the model, efforts can be focussed on identifying relational features in the output configuration, and attempting to identify them in real-world observations. This would, perhaps, resemble the kind of hypothesis-experiment procedure that characterises physical science, and ought to be the end goal of these early deliberations.

We have chosen to focus on the influence of the parameters $\lambda$ and $j$. $\lambda$ controls the importance of the trade (or more broadly, exchange, or cultural transmission) term in the Hamiltonian, changing the inclination of a site to establish a link with its neighbour. Increasing $j$ increases the cost of maintaining the population and will lead to its decrease. In practice, three graphs were created for each parameter choice, repeated to observe variation between runs. There are then three further variations of parameters, examining $\lambda = 1, 2, 4$. This set was later repeated for $j = 0.5$, with $\lambda = 2, 4$ again, so we could observe the effect of this new restraint under each of the models. $\kappa$ and $\mu$ were kept at their default values of $\kappa = 1$ and $\mu = 0.5$. Further, these outputs were calculated for each of the three models: supply, demand, gravity. Naturally, we can present only a summary of the data here.

### λ variation

The general effect on the network configuration for increasing λ is more links and larger sites. However, there are clear differences between the models. For the asymmetric models, there is a gradual, monotonic increase in average site weight with increasing λ. Most of the interaction is within regional clusters; this does not change much at higher λ values. In the supply model there is a narrow range in absolute site weights, and a somewhat greater range in the demand model. This contrasts with the gravity model, for which the range is larger. This abrupt emergence from insularity is a clear difference, and results in the development of a clearer site hierarchy. This is coupled with a reaching out between regions, as large sites see the benefit of connecting to other, albeit relatively distant, populations.

Although not marked strongly, the correlation (comparing $\text{chi}^2$ fit values) for weight and rank is better for gravity than for supply or demand alone, exhibiting the kind of site size hierarchy one might expect in a well-developed network. For this reason, this aspect of the results indicates gravity is perhaps the more physical model. Generally, there is a poor trendline fit for rank at low λ. This is probably symptomatic of the fact that many sites are poorly connected at this lower level of interaction, being cut off from the network and consequently not being visited by the random walk algorithm. Therefore, it seems fair to say that, for the rank at least, a trendline is only suitable at higher λ values. It should be noted that for all three models, varying λ does not change the basic network clusters. This is encouraging, as it suggests robustness in output due to the importance of spatial inputs.

### Population variation

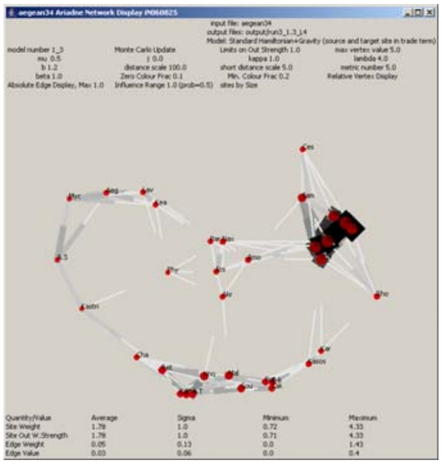
It appears that varying j has little effect on the overall qualitative picture of the network, save to reduce site sizes a little. On the face of it, it seems that increasing j (reducing population) has much the same effect as reducing λ. However, the investigation is hardly exhaustive and, as it stands, the graphs suggest only minor changes result, the underlying regional clusters being unchanged. One can again cautiously interpret this as model robustness, at least for this limited range. On the basis of the prior discussion regarding the effect of negative eigenvalues on the energy landscape, we might have expected the gravity model to be inherently more sensitive to population variation than asymmetric models. However, the only encounter of such behaviour was for large λ, zero j. In fairness, there were only two repeated runs for large λ, non-zero j, so it would be of interest to repeat several more to see if generic stability is maintained.

**Population and the length scale**

In the case of the gravity model, for large λ, where there is a reasonable level of inter-regional interaction, increasing j (increasing population costs) has the effect of removing the long, gateway-to-gateway links such as Akrotiri-Knossos. These are not weak links in terms of their strength, the network graph output suggesting they are just as strong as inter-cluster links. However, the relatively long distance they have to span suggests that this is what makes them susceptible to removal by j increase. Therefore, along with the limiting length scale set as an input (kept at the default of 100km throughout) it appears that population is an important controlling factor in the emergence of interesting inter-regional communication. A cursory examination of the factors suggests that high λ will result in greater site interaction, but that it will only extend between regions when the length scale is at around 100km, and j is not too high. Therefore, it seems prudent to suggest that careful consideration ought to be made of what an appropriate distance scale is, as it is a key factor in the emergence of interesting inter-regional behaviour.

**Variation between runs**

The overall qualitative picture between runs is generally one of overall similarity in dispersion and trendline fit, but with rather large individual site variation. Configuration characteristics such as average site weight, variance etc. do not differ much in whatever model, although there is an increasing difference between runs in the gravity model for large λ. This is probably due to the greater site hierarchy that emerges at such higher interaction levels, resulting in more variability for the largest sites as they link to big neighbours. Of particular surprise was one run (gravity, j = 0, λ = 4) in which there was a dramatic increase in site activity in the Dodecanese island cluster (see fig. 4). Perhaps this was a result of the negative eigenvalue characteristic discussed earlier. Such dramatic volatility would give one pause to consider the robustness of the model, as it would appear to be unphysical in normal conditions. However, for all its curiosity, on further runs (an additional twenty, indeed) this unexpected behaviour did not return, suggesting it was an aberration. By ordering the sites from smallest to largest, and comparing with a typical result, it was clear that the runaway growth of the Dodecanese was not at the expense of smaller islands, as the two rankings did not diverge until those last few sites.



```
input file: aegean34
output files: output/run3_1.3_14
Model: Standard Hamiltonian+Gravity (source and target site in trade term)
model number 1_3              Monte Carlo Update              Limits on Out Strength 1.0     max vertex value 5.0
mu 0.5                        j 0.0                           kappa 1.0                      lambda 4.0
b 1.2                         distance scale 100.0            short distance scale 5.0       metric number 5.0
beta 1.0                      Zero Colour Frac 0.1            Min. Colour Frac 0.2           Relative Vertex Display
Absolute Edge Display, Max 1.0  Influence Range 1.0 (prob=0.5)  sites by Size

Quantity/Value       Average   Sigma   Minimum   Maximum
Site Weight          1.79      1.0     0.72      4.33
Site Out W.Strength  1.79      1.0     0.71      4.33
Edge Weight          0.05      0.13    0.0       1.43
Edge Value           0.03      0.06    0.0       0.4
```

Fig 4. Unusual variation

All considered, it appears that the Monte Carlo method is successful in finding consistent minimal solutions on the energy landscape. While the one surprise case for the gravity model suggests there may exist the rare ‘energy trap’ for the program to fall into, these seem few and far between. Therefore it appears reasonable to have confidence in the network configurations as replicable, generic solutions for a particular parameter setting.

## Gateway site analysis

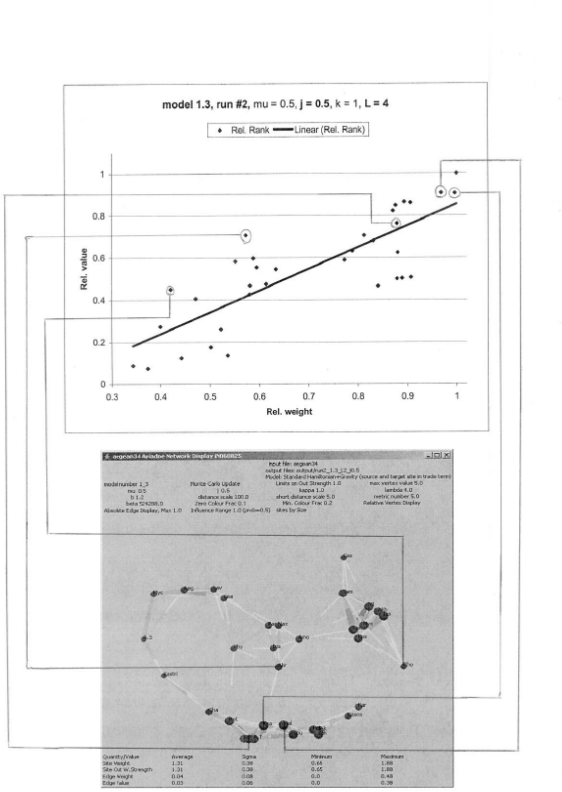


Fig. 5. Gateway site analysis. Top left: trendline outliers. Bottom left: network graphs  Right: physical system

By explicitly identifying outlier sites with their location on the network graphs, the potential connection with their spatial location and interaction strength (indicated by the width of links) became clear (see fig. 5). Five key sites were chosen for a comparison between models at λ = 4, j = 0 and 0.5. Rhodes and Akrotiri were obvious choices for gateways into the Dodecanese and Cyclades from Crete; conversely Knossos and Malia are nearest to Akrotiri and therefore ought to be the first to connect to it. In addition to these sites, Phaistos was chosen not because it is a clear gateway itself, but because it lies near to Knossos and Malia. Therefore it was interesting to investigate whether its closeness to these sites resulted in a boost or an impediment to its relative link strengths. However, Crete is modelled unrealistically in the programme: the north and the south are a great deal further apart in practice than their mere spatial location would suggest, as they are separated by mountains (blue line). Land and sea journeys require a recalibration that is currently under way.

It was hoped that by focussing on trendline plots rather than simply the network graphs, the effect of increasing j on the site's relative value (boosting or suppressing) would become clearer. It may be that the sites compensate for losing distant relationships by greater focus on their region, so that there is a negligible reduction in their interaction levels, maintaining their relative importance. Alternatively, there may be a clear loss associated with being cut off from other island clusters, as they assume more typical characteristics without their gateway benefit.  It is pertinent to note that, as mentioned before, in the asymmetric models there was less inter-regional interaction at zero j than in the gravity model. Therefore it is harder to say that changes in behaviour are due to the sites losing their gateway status. That said though, our preliminary investigations suggest that Rhodes is the only consistent outlier site.

Turning to the relative site rank values we found that, in the supply model, Akrotiri, Malia and Knossos are clear outliers at zero j. Akrotiri and Knossos lose this as j increases. In the demand model, Rhodes was the only clear outlier for all j, actually becoming an even greater deviant as j increased. In both these asymmetric cases the network graph suggests that any deviation is probably due to local interaction, with no clear inter-region links. It would therefore make sense to study the asymmetric models at higher levels of λ in future, where such links are firmly established. On the other hand, in the gravity model, there are two clear links between Knossos and Malia in the south and Akrotiri in the north. This results in Akrotiri being a very clear outlier at zero j (for both rank and strength values), with this dulled significantly but not completely as j increases.

This is a clear confirmation of the central importance to the network of gateway sites at higher levels of interaction. Therefore, if we are to start making tentative extrapolations from the programme's results to archaeological predictions, one might expect that in higher levels of inter-regional interaction, Akrotiri ought to be a prime candidate for evidence of settlement. What is key here is that it is important not because of its local site details (such as resources), *but because of its relation to other sites in the network.*

As a counter-example, it would appear that Phaistos's behaviour is generally uninteresting, fitting the trend as a 'normal' site, suggesting it gains little through its proximity to the northern Crete sites. It may be that this is a result of it being sandwiched between two other sites, sharing trade benefits with them.

## CONCLUSIONS

In this preliminary analysis, the gravity model seems to provide the results and robustness that one would hope for from a network model. This is because:

- There is (excepting rare cases) stability in solutions between runs
- The hierarchy of site sizes we might expect of such a system easily arises
- There is a healthy level of inter-regional interaction at reasonable parameter values
- There do not appear to be large changes to underlying clustering behaviour as J varies
- The type of interesting network gateway behaviour we might use to make physical predictions is forthcoming

Along with its inherent robustness, minimising the cost of our ignorance of site details, it appears sensible to continue the development of the project using the gravity approach.

In terms of what this model may tell us about patterns of cultural transmission, in these first steps it is the emergence in the gravity model of gateway sites at particular levels of population and interaction that is suggestive. This could indicate that the kinds of inter-regional interactions that characterise Minoanisation owe a lot to the emergence of gateway sites. While it would be premature to argue that gateway sites are likely to engender certain forms of regional cultural transmission, our results act as a prompt towards further investigation of such patterns in other cultural settings (e.g. Romanisation). We argue that it is not the individual, local characteristics of these sites that ‘enact’ cultural transmission, but rather the relations between sites in a network of complex interactions. Hence we advocate a macroscopic approach to questions concerning cultural dynamics that we intend to consolidate by complementing the ranking analysis of this paper with the influence matrix. However, this requires a greater realism in the network inputs, in particular a recalibration of land and sea journeys in and around Crete, as mentioned earlier.

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