# Computational models for understanding movement and territory

Andrew Bevan

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## Abstract

This paper considers a range of computational approaches for modelling human and animal movement, with the ultimate goal then being explanation of patterns in the archaeological record. It revisits traditional GIS-led cost surface analysis and highlights the need both to test such models more carefully and to make them more context-sensitive. This provides a basis for considering a case study from Bronze Age Crete and for suggesting ways in which movement models can used more imaginatively to address issues such as the development of political territories. The final discussion looks to broaden the scope of movement modelling by highlighting a range of other promising techniques and possible applications.

## 1. Introduction

The inferential leap between our recovery of a static archaeological record and our explanation of dynamic past behaviours is always going to be a challenging one, but computational and quantitative techniques can be of great assistance. This paper revisits an established method of modelling movement, cost surfaces, but also seeks to broaden the scope of current approaches to human and animal movement in archaeology by considering a range of newer methods and evidence. Discussion below begins by taking a particular position on what computational models of movement should contribute to archaeological inference. The next section then returns to the well-known method of cost surface analysis and considers how we might choose between different cost surface algorithms through controlled tests and ground-truthing, as well as how our models can better address different types of movement, loads or travel agendas. The following section then considers the important issue of how distance-based methods can inform our understanding of political geography, particular in contexts where we have no historical shortcut to the size, shape and character of political territories. The final section then suggests some future directions and possible applications for movement models.

## 2. Modelling Movement

The term 'computational model' is used here to refer to any formal model of process or behaviour that leverages the efficiency of modern computing to consider archaeological problems that might otherwise be too difficult or too time-consuming to address formally. While computational models of spatial phenomena are often implemented in a Geographic Information Systems (GIS) environment, they can also be found in less spatially elaborate software packages that offer different kinds of advantages, such as enhanced statistical or time-scheduling functionality. There have been increasing moves to bring these different approaches together through either tight or loose software coupling, but at present a certain degree of separation still remains.

An important initial question to pose is why archaeologists should bother to consider human and/or animal movement via such methods at all? Certainly the question is not an unfair one, given that many features of human and animal movement are difficult to model properly in a computer, including the detail of palaeoenvironments, our multi-sensory experiences while on the move, the often unknowable influence of social relationships on past movement patterns, or the explicit cultural meaning ascribed to certain journeys. There is therefore a risk that computational models might provide 'explanations' for movement that are entirely empty of cultural meaning. However, at their best, such models allow us to be more formal about our proposed explanations of the archaeological record, and to produce falsifiable, repeatable results.

Strategically-speaking, a model can either seek to incorporate every aspect of the phenomenon it addresses or offer a highly stripped-down scenario. A good example is the degree to which we should 'add in culture' to our modelling of movement. Given the general availability of datasets such as elevation models, there is certainly a risk that we introduce a lazy environmental determinism into our analysis. We might therefore respond by adding richer, more culturally complex variables such as culturally-encoded costs or incentives for moving through certain areas (for some good suggestions, see Llobera 2000: 71-5), However, not only will most variables of this kind involve subjective scores – assigning an extra cost for moving through what might be a taboo area, such as a cemetery or in view of a particular monument – but it is difficult to know how to combine them with other measures of cost, such as travel time or energy expenditure. More generally, the risk of hyper-real models such as these is that they can become so bewilderingly complex that they lose all explanatory strength. Constructed carefully therefore, one of the main advantages of a simple model is that it offers a null hypothesis, against which to consider potentially more complex and interesting real world patterns. To return to the example mentioned above, if there are social costs associated with passage through a cemetery landscape, they will be far more elegantly addressed by first considering the simpler case that there are none.

Having made this plea for the continued role of simple models, it is now worth looking in more detail at the most well-established computational method for modelling travel patterns and their archaeological consequences: cost surfaces. Cost surface models consider, as a first stage, the costs that accumulate with movement out from a fixed point of departure (A). As a second stage, a route can be traced on this accumulated surface back from any point (B) to the departure point (A) to suggest a ‘least cost path’. The spreading algorithm used to produce the cost surface can assume: (i) that all of the costs incurred along the way are not altered by the direction of travel (i.e. they are isotropic, such as the cost of moving through different types of land cover) or (ii) that they are operating from a particular direction (partially anisotropic, such as the effect of a strong wind on a cyclist), (iii) that they are entirely direction dependent (i.e. fully anisotropic, such as the cost of moving across a slope which varies depending on the direction in which you walk across it), and/or (iv) that a combination of isotropic and anisotropic costs are in operation.

Unfortunately, the initial hype surrounding cost surface models was justifiably tempered by the subsequent recognition of a host of methodological difficulties (see Douglas 1994; Bell and Lock 2000; Collischonn and Pilar 2000; Conolly and Lake 2006: 215-225). However, despite these acknowledged problems, there have been very few obvious efforts to test cost surface procedures prior to their use for archaeological interpretation. Without such validation, there is a real risk that published costs surfaces or least cost paths are no more insightful than the images in a kaleidoscope or the lines on an Etch-A-Sketch. The discussion that follows in the next section therefore considers a series of methods for testing the results produced by different costs surface algorithms, and then explores one fairly reliable, current implementation.

## 3. Differentiating Between Models

### *3.1 Testing Results*

An important failing of most existing cost surface routines is their inability to model anisotropic, direction-dependent costs. However, another, arguably more fundamental, problem has been their inability to produce reliable results even in the simplest of situations. Some years ago, David Douglas pointed very clearly to the acid test for cost surface models and least cost paths: their behaviour when given an entirely flat surface as input. In such a context, the spreading algorithm should be able to produce smooth, concentric bands of accumulated cost and the path delineation should produce a straight line between A and B (1994: 37). Unfortunately, most commercially available implementations produce surfaces with a heavily-faceted appearance, due to the refractory effect of the queen’s case (D8) spreading algorithm that they use to accumulate costs. The calculations of pathways across this surface therefore typically produce dog-leg routes rather than straight lines. We could happily elevate Douglas’ comment to a general principle: models should be proved reliable on simple, artificially-generated landscapes before they are deployed with any confidence on more complex topographies. The flat plain example is perhaps the most straightforward, but we might also consider how the algorithm handles a simple barrier, a simple break of slope, or a cone-shaped hill (e.g. Douglas 1994: fig.2; Minetti 1995: fig.4; Collischonn and Pilar 2000: fig.8). Indeed, some of these test cases raise important issues over how we model the trade-offs between travel-time and energy expenditure, some of which are discussed in the following section.

One relatively new cost surface implementation is GRASS GIS' r.walk module (Fontenari et al. 2005). It draws inspiration from the walking formulas first suggested by the 19th century Scottish mountaineer William Naismith and still used by hikers today as a rule of thumb for estimating travel times in broken terrain (Langmuir 1995: 39-43). In addition, it is methodologically more robust than most, if not all, other commonly available models for at least four reasons: (i) it is anisotropic in its treatment of the directional cost of terrain steepness, (ii) its spreading algorithm can adopt a knight's case (D16) search neighbourhood which leads to less refracted results, (iii) it calculates travel cost based on rates of change in the original DEM and not from a derived slope surface, and (iv) it provides output in suggested travel time rather than uncalibrated cost units. As long as the knight's case search neighbourhood is used, then r.walk module performs well (but certainly not perfectly) with a flat plain as input.[1]

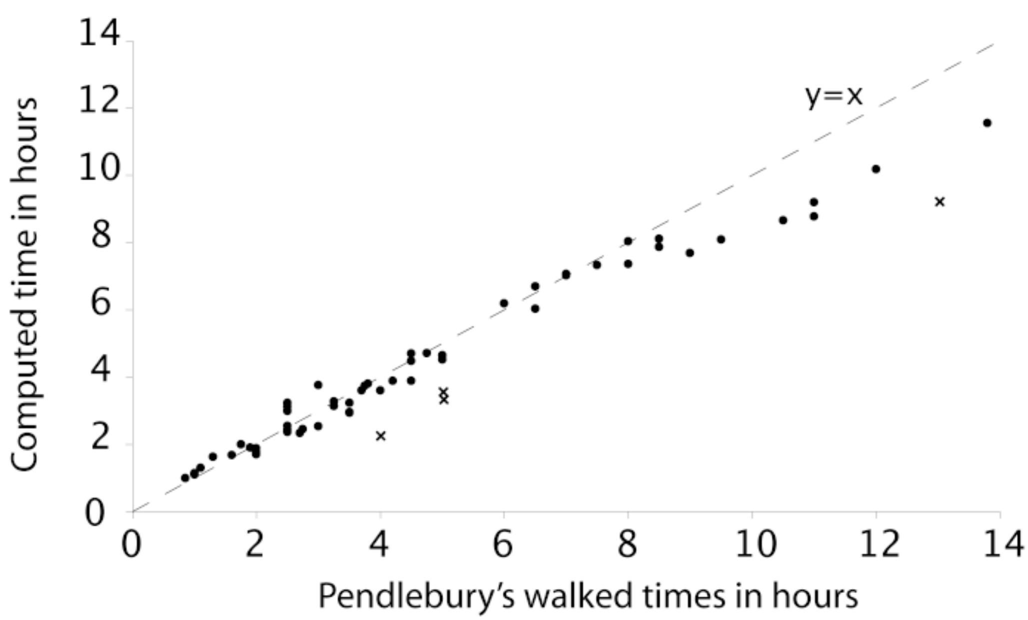


Figure 1. Comparison of the times recorded by Pendlebury for his walks between Cretan sites (n=60) and those computed by anisotropic cost surface analysis (suggested outliers are marked as crosses).

If these are grounds for thinking that this module is one of the more conceptually and practically reliable of the commonly available cost surface routines. Another

[1] Still wider search neighbourhoods are a good way of improving the situation further, but remain very computationally demanding. At the time of writing, an ongoing problem with the GRASS implementation of r.walk for delineating least cost paths is the fact that it does not produce a direction surface to force paths to be traced correctly by the companion module, r.drain. This continues to make the least costs paths produced by these procedures less satisfactory than the costs surfaces themselves. My thanks to Colin Nielsen for discussing this issue with me.

important way to validate it would be through testing against a known set of journey times. John Pendlebury (1939), for example, recorded a series of journeys he made by foot between sites across the island of Crete during the 1930s, prior to advent of major mechanized transport and road-building projects.[2] Crete offers a fairly simple environment for computational modeling of terrestrial movement. There have been few if any major rivers and only a limited number of really impassable forested zones or *maquis-garrigue* thickets. Prior to mechanized transport, pedestrian travel on Crete was mainly affected by the steepness of the terrain and the direction in which you were seeking to cross it. Figure 1 reflects the creation of anisotropic cost surfaces (in GRASS' r.walk using default parameters) for 60 sites listed by Pendlebury as starting locations and plots his suggested travel times to particular destinations against computed times. The results suggest that the correlation for journeys of less than about eight hours is very good. More precisely, while we should naturally expect that the simple variation in straight line distance between sites will account for much of the variation in these journey times ($r^2$=0.88), the anisotropic calculations offer significantly improved explanatory power ($r^2$=0.96, likely to be different from the above at $p<0.005$ using a Fisher's r-to-z transform). Thereafter, the predicted times for journeys over eight hours are often a little too rapid, probably reflecting the fact that overnight travel requires extra time for rest-stops, the burden of extra baggage, etc. Also, some journeys over extremely steep terrain were still significantly under-estimated by this model (marked as crosses). The physiological demands placed on humans travelling through such high relief, high elevation environments are substantially greater than normal, and, as discussed below, these encourage a different set of time vs. energy trade-offs. However, in spite of these anomalies, the overall results provide a very good model of direction-dependent movement through the rugged Cretan landscape.[3]

### *3.2 Providing Context*

If careful testing of cost surface results is an area where archaeologists might invest more time in future, another important way of increasing the subtlety of our modelling efforts is by being more specific about the types of mobile individuals we seek to characterise. A good start is to consider the physiology of human locomotion more directly, and in this respect, Alberto Minetti's work is particularly interesting (1995; see also Llobera 2000). He suggests that the optimal gradient for energetic efficiency is ca.6° when travelling downhill and ca.14° when travelling uphill. Some balance between these optima (probably weighted in favour of uphill ascents) typically determines the configuration of winding paths in a variety of mountainous landscapes. For example, statistical analysis of the 19th-early 20th century trackways on the Greek island of Antikythera offer support for Minetti's description:

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[2] The topographic data used here is a 15m digital elevation model of Crete, derived from the stereoscopic pairs of band 3 images of the ASTER satellite, calibrated with a series of accurate ground control points (Chysoulakis et al. 2004).

[3] If the under-estimation of longer journeys over eight hours in duration proved to be a more general phenomenon in other documented journeys, then a modifying equation of computed time to actual time could be defined relatively easily.

their prevalence across the landscape in areas below 10-12° is very consistent, but thereafter they not only become less common but also start to wind abruptly backwards and forwards, taking indirect, oblique routes to their destinations (Bevan et al. 2003: 226-9). The reason for this is presumably that their users (humans, and various animals) were creating paths that compromised between travel speed and energy expenditure.

Beyond such biomechanical considerations, we also need to be clear about whether we were are modeling average behaviour or are interested in specific agents (e.g. known individuals, women, men, old, young) who might have particular fitness levels, stride lengths, prior injuries etc. More significant perhaps with respect to the delineation of particular routes is the need to explore a wider range of possible 'optimal' paths, especially those that acknowledge the varying agendas that people have when on the move. We have already seen that it is not always possible to mimimise both travel time and energy expenditure at the same time and that some important trade-offs are therefore involved. Likewise, we could certainly model the balances struck with other goals in mind, such as avoiding injury, maximising the opportunities for detection of specific places or things (e.g. for tourism or hunting), minimising the opportunities for detection (e.g. for smuggling), or retaining the shape of a travelling group (e.g. for an army in battle order) but these have so far rarely been addressed in the archaeological literature on cost surfaces.

Many of these trade-offs are also dependent on the type of species you are modelling and the size or composition of the group involved. For example, Minetti's further work (2003) on horse biomechanics and historically-documented equine postal systems suggests consistent average speeds of ca.16km/hr and staging distances of 20-25km, both of which provided a near-optimum compromise that allowed a horse to gallop/trot for long distances, but also avoided over-exhaustion and reduce the risk of serious injury. Camel and llama caravans also seem to adopt very consistent travelling speeds (Rennell 1791; Tripcevich 2008), with the latter's optimal speed is attained on steeper slopes than humans (8-9° rather than the 6°). Group size and the amount of baggage are also important considerations in both of these cases. Baggage camels are capable of carrying heavy loads for relatively long distances, and their caravans vary hugely in size (up to thousands of camels, probably due to the flat nature of the terrain they usually covered), whereas llamas can carry far less and caravans are often around 15-20 animals (Tripcevich 2008). Donkeys travel fairly slowly but are known to be very energy efficient when carrying loads (Dijkman 1992). Given the impact of grazing animals on human movement (e.g. for hunting, herding, path formation etc.), it would also be useful to make greater use of the existing empirical data on the prevalence patterns of various grazing animals on slopes of differing steepness (for a study of North American cattle, deer, feral horses and bighorn sheep, see Gaskopp and Vavra 1987) or the types of routes they take depending on the local abundance of edible vegetation (DeKnegt et al. 2007).

A final, complicated case is the modelling of mechanically assisted movement, such as maritime travel (see also Formenti et al. 2005). Paddling, rowing or sailing between two points is often faster than terrestrial journeys, but often more unpredictable. Computational modelling is tricky because the parameters change depending on the character of the craft involved, the time of day or season, the risks the navigator is willing to take etc. In many ways, context-specific, dynamic modelling that addresses a particular historical case and accounts, probabilistically and in time-steps, for wind and current variations may be the most suitable. However, as a crude example, and as preparation for the territorial modelling discussed in the final section of this paper, we can return to the case of travel around the island of Crete. Figure 2a shows terrestrial travel times out from the Bronze Age palace at Knossos to all other parts of Crete. Figure 2b then considers the possible effect of sea voyages. Maritime travel is sometimes a rather risky business in the Aegean, one usually conducted by a knowledgeable few and prone to important diurnal, seasonal, directional and technological variations (e.g. Casson 1951). However, even if we assume an opportune, but by no means unusual, speed which is twice that typical of pedestrians on land (ca. 10 km or 5.4 knots), the resulting cost surface suggests that travel times out from Knossos to the far east and far west of the island would have been drastically reduced.

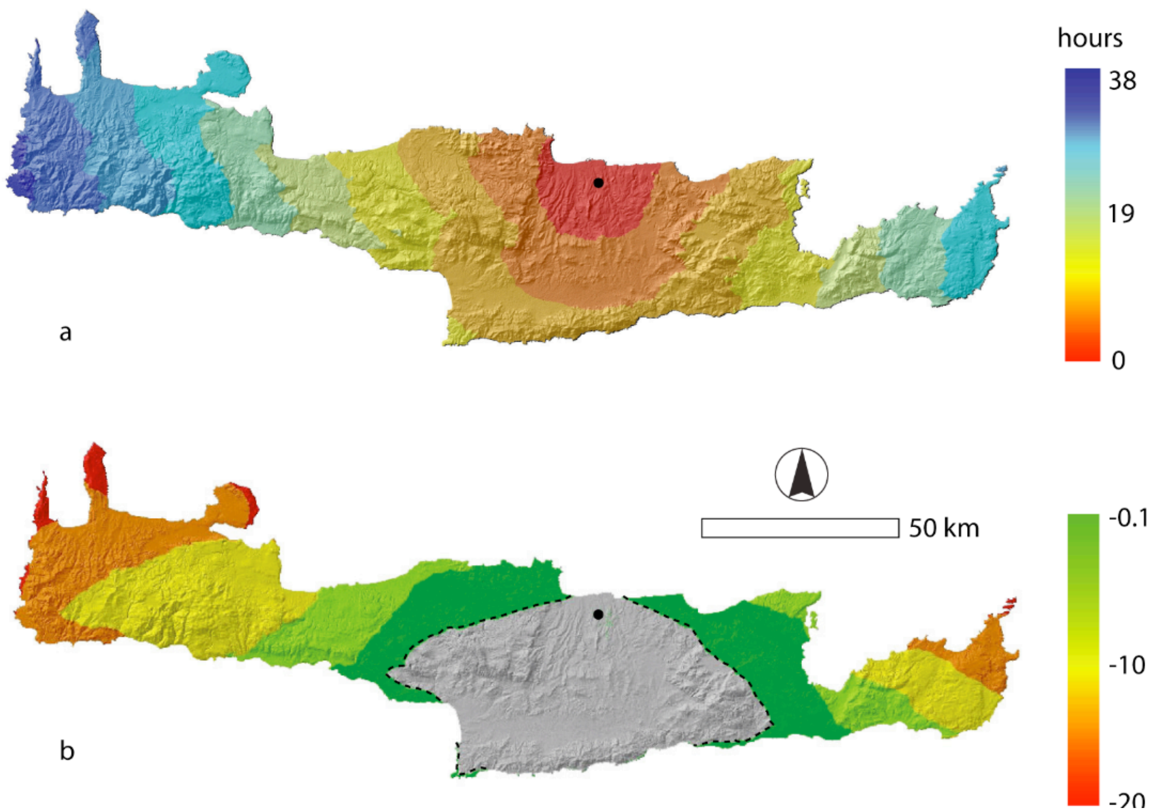


Figure 2. Anisotropic cost surfaces from Knossos: a) terrestrial travel times in hours (class breaks are every 4 hours), along with groups of linked place-names from the Knossos Linear B tablets (after Bennet 1985: fig.iii.4), b) a rough impression of the time saved by including a maritime leg in the trip from Knossos (class breaks are every hour; the dotted line marks the area with no change).

## 5. Modelling Territory

### *5.1 Background*

The way in which transport technologies and settlement configuration affect the organization of social, economic political territories has been the subject of much theoretical debate, with important contributions by Von Thunen, Weber, Christaller and Hagerstrand amongst others (see Tobler 1993; also Cherry 1987). In particular, travel time has been seen as a crucial structuring factor: for example, in an impressive cross-cultural range of contexts, there is strong empirical evidence that people spend an average of an hour of each day travelling (Zahavi 1979; Ausubel et al. 1998; Knowles 2006). This preferred amount of travel time has persisted as a deep-seated logic, despite huge increases in the *distances* that people travel with the aid of faster, more efficient modes of transport. Such preferences arguably have a consistent logistical impact on the size and scale of agricultural catchments in sedentary farming societies, even if the agricultural strategies themselves can vary dramatically over time and space.[4] This means that we can certainly use (carefully calibrated) computational models to improve our understanding of these catchments. However, the discussion below, briefly considers the, arguably more difficult, challenge of how we might model formal political territories. It revisits the idea of using costs surfaces to calculate irregular zones of political influence, but suggests several new ways in which this might be done productively.

The more straightforward case of territorial modelling is the one where we assume potentially equal allocation between sites of supposed equal status (i.e. peer polities, Cherry 1986). The example below continues to use Crete as a case study and begins by considering the possible case of peer polity interaction during the Protopalatial period (ca.1950-1700 BC), before then moving on to consider methods for developing explicitly hierarchical models in situations where we might suspect more complex patterns of political dominance (such as for Crete during the Neopalatial period: 1700-1450 BC).

[4] Several studies of recent (but pre-mechanised) Greek farmers have suggested a similar one-hour round-trip threshold by documenting an average maximum distance to fields of 2.2km (Wagstaff and Auguston 1982: 109-10; Bevan et al. 2003: 230).

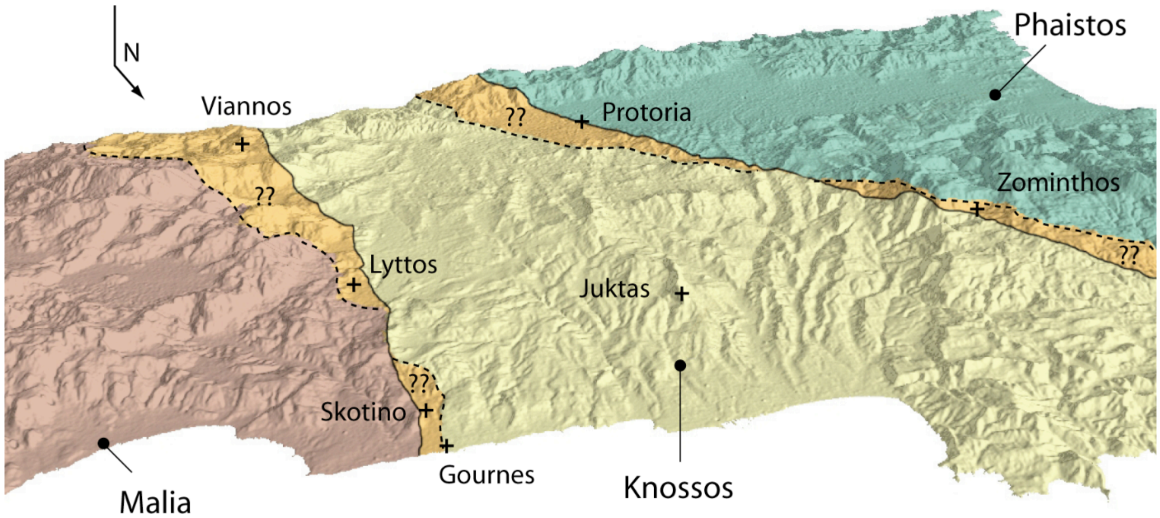


Figure 3. Perspective view of possible territorial allocations for three major central Cretan palaces, based on travel time: Knossos, Phaistos and Malia. The solid black line represents the border drawn between them where the computed travel costs are anisotropic, while the dotted line represents the border when an isotropic model is used. The zones in-between, whose affiliation changes depending on the model, have been labelled with ?? for clarity, and a few other locations have been added for context.

### *5.2 Peer Polity Models*

Figure 3 considers the three major palatial sites of central Crete in the Middle and Late Bronze Age and suggests the territory that might be allocated to each one, were we, for the moment, to ignore the political role of any smaller communities and to assume that each major centre exerted equal political or economic influence. Even if we intend to keep our modelling deliberately simple, and consider only the impact of topographically-afforded movement on the territorial allocations, it is not clear that we should always prioritise directional travel out from the centre (the anisotropic case in modelling terms) as the key factor. It is therefore interesting to compare the territories drawn on the basis of anisotropic cost surface models for each of the three major sites, with those derived from a more traditional, isotropic model. As discussed above, the latter is not a very satisfactory way of calculating directional travel, but it might still be relevant for assessing the more complex logistics of multi-directional exchanges (e.g. the criss-crossing activity along different border zones). Combination and comparison of the results of these two anisotropic and isotropic approaches suggests broad agreement with respect to territorial allocations, but also certain areas of the landscape that we might consider as potentially contested spaces. In such places, local affiliations might vary depending on what form of interaction was involved, and a good example is the uncertain area around Gournes (where various commentators have mentioned the mixed Knossian and Malian stylistic references of the decorated Protopalatial pottery: Cadogan 1994: 61) and which also encompasses the important ritual cave site at Skotino. More generally, the occupational histories and local affiliations of other intermediary locations (such as those labelled in figure 3) might benefit from closer attention with these issues in mind.

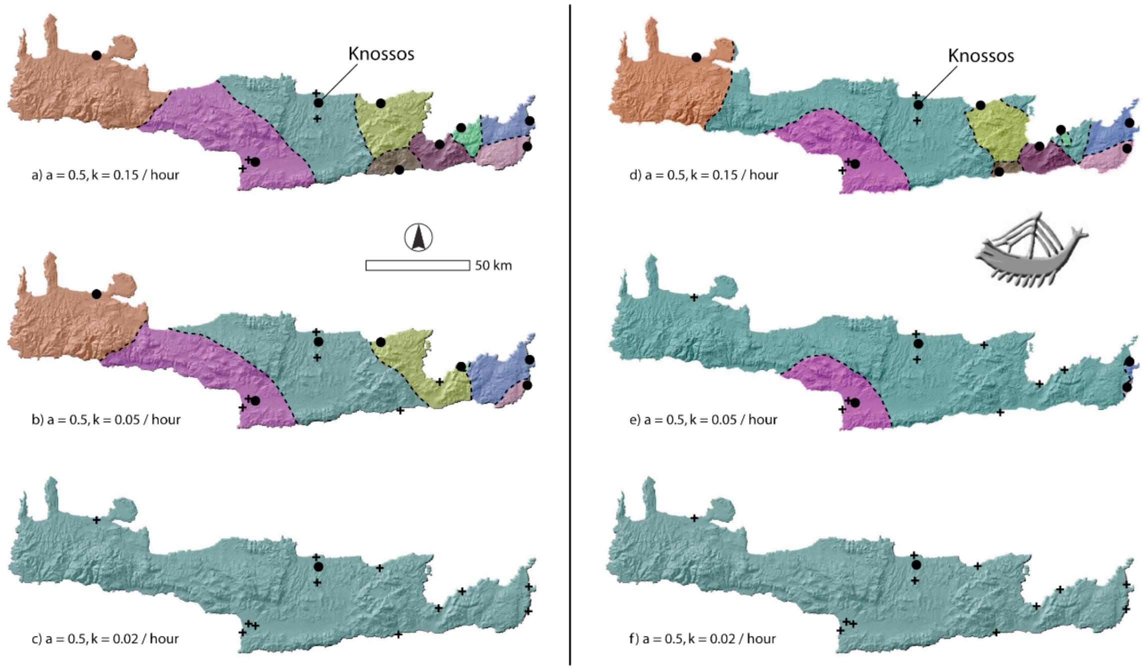


Figure 4. Six cost-weighted territorial allocations according to the Xtent model: a-c) terrestrial travel only, d-f) maritime travel allowed for Knossos only (at 5km/hr). Dominant centres are shown as solid circles and subordinate ones as crosses.

### *5.3 Hierarchical Models*

So far we have considered territorial allocations in which only one centre was concerned (figure 2), or where each centre was considered equally-influential (figure 3). Of course, real world political and economic landscapes also reflect patterns of hierarchical dominance among sites and there are several ways in which these might be modelled computationally. Rihill and Wilson (1991) suggest an attractive method that simulates the growth of central places through the spatial networks of what are initially peer-to-peer interactions. While this has the clear advantage of deriving its measures of political influence from the spatial configuration of settlements itself rather than assigning them from the outset, it does assume that we have fairly comprehensive knowledge of the settlement network. In contrast, Renfrew and Level proposed an Xtent model (1979) that requires empirical assessment of individual site influence, but does not demand such detailed knowledge of all levels of the settlement landscape. They suggested an equation, $I = C^{\alpha} - k.d$, where, at a given location in the landscape, the influence ($I$) exerted by a particular site can be expressed as a function of the relative size of a site ($C^{\alpha}$), and its distance away from the location of interest ($k.d$). The exponent $\alpha$ is used to re-weight site size (i.e. either amplifying or dampening down relative size differences) while $k$ models the rapidity with which influence decays with increasing distance. Ideally, both of these weighting variables should be determined empirically by assessing them first in known political contexts and similar socio-economic circumstances. However, several commentators have suggested that there are practical and theoretical justifications for using 0.5 as a working value for $\alpha$ (e.g. Renfrew and Level 1979: 157-8). Likewise, values for $k$ that express a decline in influence of between 0.5% and 3% per kilometre of horizontal distance travelled have been plausibly suggested as an experimental bracket (Grant 1986: 21-24; Renfrew and Level 1979: 151-166; Scarry and Payne 1986: 83-4).[5]

While Renfrew and Level acknowledged the desirability of considering more topographically sensitive measures, their original implementation assumed Euclidean ('as the crow flies') distances between sites. However, both recent Open Source software development (Ducke and Kroefges in press) and the empirical testing of the Cretan cost surfaces using historically-documented travel times (see above), encourage us to consider a topographically-sensitive version. The palace centres of central Crete were of arguably similar size in the Protopalatial period and hence perhaps amenable to peer-polity assumptions used in figure 3, but in the following Neopalatial period, there are reasons for thinking that Knossos may have been both larger than the others and more culturally dominant. Figure 4 explores the possible implications of this with a series of Xtent allocations, bracketing three different values of $k$; using the estimated area of each Neopalatial town as a proxy measure for its overall social, political and economic influence, and taking r.walk surfaces as an indication of travel time.[6]

These results offer almost the full gamut of plausible political outcomes, from segmentary partitioning of the Cretan landscape to complete control by the palace at Knossos, with the added suggestion that any shift between these two possible modes of organization might by quite abrupt and sensitive to small-scale changes. In fact, the current model assumes the most egalitarian possible size relationship between Knossos and its largest competitors and relatively small downward changes in the size for the less-well defined Neopalatial sites at Phaistos and Malia are sufficient to induce patterns of greater Knossian dominance. Likewise, any

[5] For the analysis below, this suggested range for $k$ was transformed into travel time values between 2% and 15% per hour (assuming the standard estimate of unimpeded travel on the flat as ca.5km/hr). The Chinese strategist, Sun Tzu (VII.9-10) can be interpreted as suggesting a 2-3% drop in effectiveness for each kilometre a pedestrian army was made to manoeuvre, and more generally, Renfrew and Level's approach shares similarities with other models for the decline of political influence and/or military force with distance (e.g. Boulding 1962: 227-47; Stinchcombe 1968: 216-30; Turchin 2003: 17-19). As formulated by Renfrew and Level and as implemented here, the $k$ value assumes a uniform linear decline in influence with distance – in many respects however, a more appropriate distance decay model should offer the possibility of thresholded and/or non-linear decay (e.g. exponential or logistic).

[6] As in previous studies, the site sizes were divided by the size of the largest centre to standardize them. The calculations for site size are taken from Whitelaw 2001 with minor modifications (D. Puglisi, S. Müller-Celka and V. La Rosa pers.comm.). One important possible gap in the evidence is the Rethymnon-Vrysinas area where we might expect, but cannot yet document, a major settlement and palace to have existed.

major improvement in the efficiency of communication across the island (which could plausibly be modelled by decreasing the *k* factor) is also likely to have promoted the centralising ambitions of the largest centre, particularly if you assume unequal access to these new travel opportunities. A good example might be the construction of a formal road network, but an alternative explored here is the impact of differential access to a maritime fleet. If we allow Knossian influence to propagate not just by land but also by sea (using the slow estimate for maritime travel used in figure 2b), the results change dramatically (figure 4d-f), with far more rapid propagation of political power to the far east and west of the island. Differential maritime control may therefore be a key issue as, not only is there a strong, if highly speculative, later tradition of an active Knossian fleet (the 'thalassocracy of Minos'), but in historically-documented periods prior to its inclusion into the modern Greek state, Crete has only been controlled as a single unit by those that did so through naval power (Rome, Venice and Istanbul; notably all external states however: Bennet 1990).

## 6. Future Directions

This paper has addressed issues of how we validate cost surface models, how we make them more context-specific, and then how we might deploy them to get a better understanding of political territories. While there will continue to be many archaeological situations in which this kind of global assessment of movement and its socio-political implications will be useful, in future, it will also be increasingly important to integrate or complement these techniques not only with a broader literature on the sociology and biomechanics of movement, but also with other analytical techniques that offer more configurational or situated perspectives. For example, various techniques in spatial statistics might benefit from substituting ordinary straight-line distances for topographically sensitive measurements (e.g. for multi-scale, point pattern analysis such as Ripley's K: Bevan and Conolly 2006: 229). In this case however, there remains a methodological clarity to the existing Euclidean space that should not be discarded without some careful thought, and in the short term, the calculation of topographically-weighted distances, on the fly and in any number of possible directions, would add very significantly to computational demands.

Far more tractable however are the limited number of discrete interactions modelled by network analysis. Such an approach can address discrete node-edge relationships in the real world (e.g. a road system or computer network) or can be abstractions of more complex patterns of interaction (e.g. between social actors in a community). In archaeology, it has been used to look at Roman itineraries and regional interaction networks (e.g. Isaksen 2008; Evans et al. 2007). Cost weightings can certainly be attached to each of the inter-node links and travel time is regularly incorporated for applications in urban geography or delivery management. Interactions in more complex landscapes are trickier given that the range of movement is much larger and the nodes often less clear-cut. However, network analysis using settlements as nodes and travel times between them as distances is certainly possible. More broadly, although landscape archaeologists now rightly emphasise the need to think of archaeological landscapes as continuous rather than merely site-based, there are still grounds for seeing some underlying topological structures at work. In more rugged landscapes for example, ridgelines cross each other at peaks, channels cross each other at pits, and channels cross ridges at passes. These landforms thus create something akin to a network structure that is highly visible and can be shown to have a noticeable impact on human orienteering (Maxwell 1870; Wood 2000). Likewise, traces of existing trackways are a kind of landscape capital that has far-reaching consequences in terms the way movement becomes configured in otherwise undifferentiated terrain (Helbing et al. 1997; Bevan et al. 2003: 226). Landscape topologies such as these are networks that lend themselves to verbal narrative, conveying geographic information in a way that mirrors the users own situated experience. In this respect both the fixed nodes (e.g. recognisable places) and the edges that connect them (e.g. proverbial 'high roads' and 'low roads') are far more easily ascribed cultural meaning. One methodological caveat however is that spatial narratives of this kind tend to be purpose-specific: the paths they describe are sometimes indirect and sub-optimal from a purely physiological or topographic perspective, but more reliable and repeatable in the absence of complex navigational devices.

If the combination of fixed network models and real world variables such as travel time offers some great opportunities, then there is similar potential for enhancing the results produced by agent-based simulation. The latter offers an extremely attractive way to consider the dynamic behavioural relationship between individuals (e.g. people or households) and larger-scale structures (e.g. societies, ecologies). In archaeology, it has been used to consider colonisation strategies, settlement dynamics and exchange relationships amongst other things (Lake 2000; Kohler et al. 2000; Bentley et al. 2005; Conolly et al. in press). At present, agent-based modelling is often performed in fairly abstract environments (e.g. fixed networks of interaction or Euclidean spaces), but their ability to model situated decision-making, based on information sharing, inheritance, changing conditions and/or imperfect knowledge also makes them ideal for considering a range of archaeological problems, especially those in which movement over variegated terrain is involved (e.g. colonisation, way-finding, exchange relationships, the spread of ideas). In particular, agent-based models provide an important, if as yet not fully-exploited, antidote to the global, top-down approach implicit in cost surface modelling.

In any case, it is arguably the combined use of traditional cost surfaces and these newer methods to address carefully defined and theorised problems that offers the most promise for future archaeological research.

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