Pattern to process

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CHAPTER 6

LINE-OF-SIGHT AND COST SURFACE ANALYSIS USING GIS[*]

1 INTRODUCTION

This review article assesses the majority of accessible archaeological studies based on two GIS techniques (viewshed analysis and cost surface analysis) over the decade 1990-2000. The two techniques are taken together because of certain similarities in methodology and underlying theoretical principles, which express an emphasis on the human experience of being and moving in the landscape; not surprisingly, these techniques have been at the centre of processual – postprocessual debate almost from the beginning.

1.1 AIMS

This paper reviews published work in two related areas of GIS application in archaeology – line-of-sight analysis (LOSA) and cost surface analysis (CSA). Line-of-sight analysis uses the ability of most GIS to calculate the intervisibility of two given points on a given digital elevation model; cost surface analysis uses cost accumulation algorithms to calculate the cumulative cost of travelling over a digital cost landscape. These two techniques have received much attention in recent years, first because they were seen to be implementations of well-established 'processualist' analytical procedures, and latterly because of their supposed potential to escape from naïve quantitative processualism into 'enriched' qualitative post-processualist (post-structuralist) types of analysis. Because it provides the context for much current work, this debate is summarised here in section 1.2. However, as I hope to show in this article, the theoretical affiliations and rhetoric of the various researchers appear to have little influence on the practicalities of implementing GIS-based LOSA and CSA; rather, it is the type of question that is being asked that determines methodological possibilities and constraints.

The larger part of this article (sections 2 and 3) is therefore concerned with reviewing *procedural* aspects of CSA and LOSA studies.

The field of CSA and LOSA has reached a stage where stocktaking has become useful (see, for example, Van Leusen 1999, Witcher 1999, Wheatley & Gillings 2000, in press). A subsidiary aim of this review has been to provide the reader with a starting point for locating case studies and methodological studies relevant to their own research – hence the extended bibliography section.

[*] An earlier version of this article, dealing with developments up to about 1998, was published in the proceedings of the 1998 Annual Meeting of CAA (Barceló et al. 1999), but this has been substantially revised and updated for the current version. In conjunction with this article, two other chapters in my thesis (15 and 16) present case studies conducted over the years in order to investigate aspects of 'dominance', territory, and accessibility arising from archaeological thinking about the role of Late Iron Age hillforts and markets in the Wroxeter hinterland (UK), of early Roman colonies on the Lepine Margin (Pontine Region, central Italy), and of Middle Bronze Age to Early Iron Age settlements in the Sibaritide (southern Italy).

Much of the work discussed in this review has only comparatively recently become accessible in the form of published proceedings (Dingwall et al. 1999, Barceló et al. 1999, Gillings et al. 1999, Lock 2000, Stancic & Veljanovski 2001) which, however, tend to give voice to a specifically Anglophone community. Although I have tried to alleviate this bias by also including examples drawn from work done elsewhere, I cannot claim to have succeeded in this. I hope that my emphasis on the methodology rather than the content of the examples has palliated the effects of this failing. Furthermore, I have taken care to include the work and views of non-archaeologists (geographers and landscape planners in particular), as well as materials that are only available on CD-ROM (Dingwall et al. 1999, Johnson & North 1997).

1.2 THEORETICAL CONTEXT

Following an initial period in which an increasing number of archaeologists experimented with the use of GIS to grapple with a variety of questions, many critics argued that the naive use of GIS has led to a revival of *environmental determinism* (an issue discussed more fully in Gaffney & Van Leusen 1995), and have advocated a post-processualist approach to using GIS. The root of the problem was seen to lie in the geographic approaches from which GIS were built, in which space was treated as an abstract geographical concept ('Cartesian space'). As Llobera (1996) puts it, there is no observer, no perspective, and no history in this kind of space. The alternative, post-processual concept of space has, by contrast, been 'humanised': space derives its meaning and properties from the presence of observers.

Others think however that despite appearances, GIS can be used in various ways for the modelling of cognitive landscapes (Wheatley 1993, Taylor & Johnston 1995). Attempts to address the perceived rigidity of current GIS applications include the incorporation of concepts of uncertainty (Gillings 1996, 1998, Loots et al. 1999, Nackaerts et al. 1999), the ideal organisation of space and society (Zubrow 1994), time and change, and of affordances (Llobera 1996). This is signalled as an important current development in the *GIS Guide to Good Practice* (Gillings & Wise 1998), but it is not yet clear what, if any, improvements these approaches will bring. This issue is discussed in more depth in section 3.3.

What makes us think GIS can be used in reconstructing past landscapes? The landscape, both in the past and in the present, is structured by the fact that resources are distributed unequally over it. This applies to both natural and social resources - drinking water and infrastructure are only available in some places; good farming and stock rearing land is not available everywhere or is already occupied by others; centres of political power, civic administration, and ritual significance are few and far between. People's choices both structure this 'resource landscape' and are structured by it, and we therefore expect archaeological remains to exhibit structuring of this type. Viewshed and cost surface analysis are two ways to reveal such structuring.

The latter has aroused widespread scepticism about the usefulness of GIS in archaeological research as, for instance, at the 1995 meeting of the UISPP (Bietti et al. 1996; Johnson & North 1997; reviewed by Bampton 1997). A balanced outsider view of the issue can be found in Taylor and Johnston (1995), who placed then current uses of GIS in the context of the 'quantitative revolution' and the 'New Geography' that took place in the 50s and 60s. These authors provide a useful and provoking discussion of the dangers of much current data-led GIS use but also stress the potential – mainly in pattern analysis (see also Gaffney & Van Leusen 1995).

Whilst American researchers have tended to continue in this processualist tradition, much recent European work, largely driven by a British post-structuralist school, stresses humanistic (as opposed to abstract, Cartesian) forms of spatial reasoning. The latter rely heavily on LOSA and, to a lesser extent, on CSA for modelling past perceptions of the natural and human environment. Hermeneutics (the art of interpretation) has been put forward as offering a theoretical basis for viewshed analysis in particular (Lock et al. 1999:61). Thus, philosophical positions appear to be irreconcilable at the moment. On the other hand, it is not clear that these positions result in substantially different approaches to LOSA and CSA. Post-processual contributions may be replete with references to Bender's (1993) edited volume on landscape perspectives and Tilley's *Interpretative Archaeology* (1993) and *Phenomenology of Landscape*

(1994); talk may be of 'perception' and 'meaning' rather than of 'viewsheds' and 'patterns', of 'the hermeneutic spiral' rather than of 'exploratory data analysis'; but there the differences end. As Tschan et al. (2000:33) remark, many recent theoretical 'advances' are entirely devoid of any current methodologies or even of the potential of such.

Rather than classifying LOSA- and CSA- based studies on the basis of –isms, a more fruitful approach would be to look at the subject matter (type and amount of archaeological data, geographical and temporal scale) and research aims. Accordingly, two types can be distinguished:

- At a relatively local scale, students want to explore cognitive space around single monuments or synchronic/diachronic systems of monuments. This type of study often has a dynamic component, either in space (movement) or in time (creation of monumental landscapes). The objective is to explore what is *unique* about the situation.

- At regional scales, students are intent on using social/cognitive variables in order to build models that allow us to detect and explain observed patterns site locations and attributes. Here, the objective is to explore *similarities* between situations, and models are typically static and quantitative in nature.

The former, qualitative, approach seems most useful in situations where high quality archaeological data are available, whereas the latter represents more of a continuation of the quantitative deterministic approach - albeit with the use of an enlarged set of variables to play with. In this regard it is noteworthy that *qualitative* GIS models are nearly all based on well-studied landscapes replete with monuments and symbolic meanings.

The aim of the current review of methods is to allow us to turn our attention to the more fruitful task of answering archaeological questions. But there is also a second reason for reviewing current archaeological applications of viewshed and cost surface analyses - archaeological arguments that are ultimately, if only partly, based on their outcome become invalid if they have been improperly applied or if the results have been wrongly interpreted.

1.3 CSA AND LOSA: TWIN TOOLS FOR COGNITIVE LANDSCAPE ANALYSIS

The reader might wonder why the two separate techniques are discussed together. Although they are superficially different, viewshed and cost surface analyses are intimately related techniques because they both define aspects of the social space surrounding an observer. Take, for example, territorial markers. These must be highly visible (though not indiscriminately so, as we shall see below) and also be located at the edge of some kind of 'territory'. The former is modelled through LOSA, the latter through CSA; the two cannot be separated.

A more abstract way of looking at the relation between the two techniques would be to note that both are based on the notions of *focus* (in the sense of a point-like location which might be the current or intended location of the protagonist, or might have a significant level of visibility or accessibility) and *direction* (as in megalithic alignments pointing at midsummer sunrise points, or in the travel networks discussed below). As was recently pointed out by Wheatley and Gillings (2000:4), post-structuralist theory provides another argument for linking the two techniques, in that *perception* is meaningful only to *mobile* observers.

Such interrelations are expressed, consciously or unconsciously, in studies that combine both types of analysis in order to construct an archaeological argument. See, for example, the work of Gaffney et al. (1996a, 1996b:37-8), where cost surface derived catchments are compared with viewsheds of Iron Age hillforts on the Dalmatian islands; the suggestion in Belcher et al. (1999:98-100) that Archaic tombs around the urban settlement of Nepi in Tuscany are situated in areas difficult to reach while easy to see; Madry and Rakos' (1996:123) use of the visibility of Roman roads from hillforts in Burgundy as an input variable for cost surface analysis; and Llobera's (2000:72-5) use of viewsheds to define 'attractive' and 'repellent' factors influencing movement near certain types of monuments.

2 COST SURFACE ANALYSIS

2.1 PRINCIPLES AND APPLICATIONS

'Cost surface analysis' is here used as the generic name for a series of GIS techniques based on the ability to assign a cost to each cell in a raster map, and to accumulate these costs by travelling over the map. Early examples were published by archaeologists working with the Arkansas Archaeological Survey and the US National Parks Service (Limp 1989, 1990). Cost surface analysis is rooted in traditional site catchment analysis, introduced to archaeology by Vita-Finzi and Higgs (1970), who wanted to study the economic basis of prehistoric life by looking at optimal foraging models of resources available within a *catchment area* or territory associated with a settlement[1].

The first step in site catchment analysis is to derive a territory (catchment) belonging to a given focus (site) by applying some geographical rule. In its simplest form this would be a distance rule, resulting in circular catchments with a typical radius of 5 or 10 km. The second step is to analyse the properties of the catchment area, usually to see what economic benefits (e.g., agricultural yields) would accrue to the focus. The radius would be chosen by experimenting with actual travel times, or by reference to ethnographic data (Chisholm 1968). Deriving a circular catchment area within a GIS is a trivial operation, and reporting and tabulating the presence of variables within each catchment can be automated. Recent examples can be found in Saile (1997) and Lock and Harris (1996:234-8), who used such buffers to model areas of in- and outfield agriculture around Iron Age Danebury hillfort. A more sophisticated form of such analysis is the construction of distance buffers around the focus, allowing a statistical analysis to see if some archaeological correlate gravitates significantly toward or away from it. One well-known example of this is Hodder and Orton's (1976) calculation of the distance distribution between coins and Roman roads in southern Britain[2]; a very similar application with an interesting twist in the tail was presented recently by Rajala et al. (1999), who interpret the correlation between site locations and distance to Roman roads as indicating discovery biases.

Closely related to catchments are *tessellations*, which have a more specific and theory-laden meaning. Whereas catchments are generally used to describe economic characteristics of the archaeological landscape, tessellations of archaeological landscapes are used to postulate a social (political, administrative, religious) structuring – for example, in Renfrew's (1986) peer polities. The most widely known traditional method for doing this is the calculation of Thiessen (Voronoi, Dirichlet) polygons. These are based on a simple nearest-neighbour method for partitioning a featureless space, equivalent to a gravity model operating in 'Flatland', and result in a complete tessellation of space. Both traditional catchments and tessellations rely on the simplifying assumption that the landscape is a flat, two-dimensional space, and resistance to movement across it is isotropic (the same in all directions). They also result in choroplethe maps rather than mapping the continuous fall-off of variables such as accessibility and control. In a real landscape the size and shape of a catchment area or territory would be much more variable, depending on the nature of the terrain, the topography, and a host of other factors. In a real landscape, the economic use of, and social control over, an area becomes less with distance rather than suddenly switching from yes to no (1 to 0) as the boundary of the catchment or territory is crossed.

Cost surface analysis provides a way out of this by allowing the simple 'flat' geographical space to be supplanted by a set of complex cost surfaces incorporating many relevant properties of the terrain. It also allows for the distance- and gravity based rules for defining the catchment or territory boundaries to be replaced by a time- or energy expenditure based rule for accumulating costs. As the resulting cumulative cost surface is a continuous raster map, any number of values may subsequently be used to provide 'cut-off points' or boundaries to the catchment or territory. Alternatively, cost accumulation starting at multiple points may be allowed to run on until all available space has been used, in which case a tessellation of space similar to Voronoi tessellation has resulted. For example, Verhagen et al. (1999) calculate cumulative travel time in order to construct 'accessibility catchments' which are then used as an input variable in a predictive settlement model. Stancic (1994) Stancic et al. (1995) compare and contrast all three methods (Thiessen polygons, circular catchments, and cost-derived catchments) using protohistoric settlement data from the Dolenjska region in Slovenia. As we shall see in the next section, the possibilities offered by this technique have led to some confusion as to the best way of calculating costs.

2.2 ALGORITHMIC CONFUSION

Employing a simple radius to define a catchment area is equivalent to travelling over a flat cost surface; accumulation in this special case is constant in all directions and the maximum horizontal distance therefore defines the boundaries of the catchment area. If accumulation from a number of starting points is allowed to continue until the entire cost surface is covered, a Voronoi tessellation results. Just as the traditional method can be modified to employ travel time as a limiting factor, so cost surfaces can be modified to reflect the difficulty of travelling over various types of terrain. Accumulating such costs will result in irregularly shaped catchments for any particular total energy expenditure. This principle can be extended so that any combination of factors can be used to define costs, and any combination of criteria can be used to derive a cumulative cost surface from those costs. Exactly how all this should be implemented is a question that seems to have been answered differently by each individual author. In the published research there is a wide variety in the parameters used to calculate cost/energy surfaces and in the algorithms used to perform cost accumulation - a sign of the immaturity of the field.

A further refinement of the technique, originally discussed by Renfrew and Level (1979) as 'XTENT modelling', would result from assigning differential weights to the sites or *foci* of the catchments, so that accumulation proceeds with different degrees of ease over any particular cost surface. Ruggles and Church (1996) first applied it in a GIS context in a weighted Thiessen tessellation of their Mexican study area, but no implementations using CSA have been published as yet.

Most studies have relied exclusively - and continue to do so - on slope as the factor determining cost (e.g., Gaffney and Stancic 1991, Gaffney et al. 1993, Massagrande 1996, 1999, Bell & Lock 2000). This may work in areas where topography has an overriding effect on human behaviour; see, for instance, Huckerby's (1999) study of how well four rival foraging theories fit with the costs of accessing mammalian resources in Queensland, Australia. But more realistic calculations, based on physiological measurements of energy expenditure on different types of terrain, are now feasible and have recently been employed in several studies (see below). A recent comprehensive review of the literature on all forms of walking is contained in a volume edited by Rose and Gamble (1994).

Some authors have attempted to derive costs inductively, from archaeological observations relating to actual territorial boundaries or actual distances travelled per time slice. One example of this is the work of Glass et al. (1999) and Anderson and Gillam (2000), who derive costs from observed dates of first occupation of North and South American sites, and assume that the 'delays' between colonisation of successive areas are caused by the cost of travelling from one to the next. Apparently no universal set of absolute real-world travel costs is to be found in the literature, but this need not be a problem so long as a universal set of relative costs can be found.

Travel cost surfaces can be isotropic (the same in all directions) or anisotropic[3]. Because of the effect of both slope and terrain, the cost of traversing a particular location may differ depending on which direction it is being crossed in. Crossing cells representing a river is an obvious example of terrain anisotropy - travelling down-river in a boat incurs different costs from travelling up-river, and different costs again when crossing the river. Surprisingly, until very recently raster GIS did not provide the functionality to introduce anisotropy; a closer merging with the functionality generally present in vector GIS seems needed. Examples of models based exclusively on isotropic cost surfaces can be found in Savage (1990); Rajala (1998) mapped territories in the Ager Faliscus using an isotropic cost surface derived from slope and based on empirical walking effort data; finally, Bell and Lock (2000:88-9) derive the *relative* isotropic slope-related cost from the ratio between its tangent and the tangent of 1°, assigning the latter a cost of 1. Thus, the cost of ascending or descending any slope ? is determined by the formula

$$\tan(?) / \tan(1°)$$

which produces a non-linear relation between slope and cost (also visible in the downslopes of figure 1), becoming significant on slopes steeper than about 25°.

However, most authors agree that travel cost has both an isotropic and an anisotropic component; the former exemplified by costs relating to the type of terrain (soil, vegetation, and wetness), the latter by costs relating to slope and streams. Verhagen et al. (1999) calculate the accessibility of settlements in the Vera Basin, Spain, on the basis of slope according to a formula provided by Gorenflo and Gale (1990). They specify the effect of slope on travelling speed by foot as:

$$v = 6\ e^{-3.5\ |\ s\ +\ 0.05\ |}$$

where v = walking speed in km/h, s = slope of terrain in degrees, and e = the base for natural logarithms. This function is symmetric but slightly offset from a slope of zero so the estimated velocity will be greatest when walking down a slight incline. Bell (Bell et al. 2002) also employs an anisotropic cost surface based on slope to generate a cumulative path network between Samnite sites in central Italy.

It should be noted that anisotropic functions only work if the direction of travel is taken into account – otherwise they revert to isotropy. For instance, the variable representing slope in the Gorenflo and Gale formula (above) has to be signed in order for the slight 'preference' for downslopes to emerge. Introducing anisotropy in slope costs is not trivial, and recent approaches, which are based on the capability of GIS to generate aspect (direction of steepest slope) maps, are forced into making simplifying assumptions about the direction of travel. Bell and Lock (2000:90) introduce anisotropy in slope related costs by interposing an aspect checking step – cutting costs by 50% for 'angled' ascents and benefits by 50% for 'angled' descents[4]. Likewise, the isotropic formula

$$\text{Effort} = (\text{percent slope}) / 10$$

was modified by Hayden (pers. comm.) into an anisotropic formula by calculating full cost upslope, no cost cross-slope, and half-cost downslope. Hayden then added an isotropic cost layer for different terrain types and terrain roughness (calculated as the change in slope). However, the best published work in this regard is by Krist (2001a,b), who used the general orientation of historic native American trails in Michigan to determine which aspects represent up, down, and sideways. On this basis he calculated an adjusted slope S_a using the formula

$$S_a = S * \cos(A_t - A)$$

where S and A are the original slope (in percent rise) and aspect values, and A_t is the direction to the starting point. The multiplier $\cos(A_t - A)$ ranges from –1 to 1, generating negative values for downslopes while attenuating the effect of sideslopes. To convert the adjusted slope values into cost surfaces representing energy expenditure in kcal, they and a constant for average human walking speed of 100m/minute were entered into McDonald's (1961) three physiological equations for topographic energy expenditure[5]. The resultant cost surface could then be combined with a second, terrain, cost surface representing additional barriers thrown up by lakes and wetlands.

Because anisotropy was introduced into the cost calculations, Krist then had to repeat them for both directions of travel along each trail segment. A very similar approach was taken by De Silva and Pizziolo (2001), who adapted an anisotropic function deriving from backpacking (Ericson and Goldstein

1980) to calculate a maximum friction surface for round trip movement in the Neolithic of the Biferno valley (Italy), modifying it to:

$$\text{effective friction} = \text{stated friction}^{|\cos\hat{}k\ ?\ a|}$$

where ^k is a user defined coefficient (2 for movement on foot), and ? a is the difference in degrees between the walking direction and the direction of maximum friction.

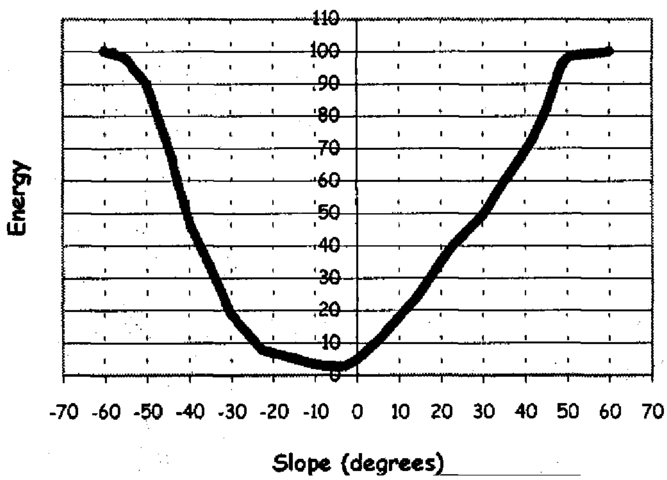

Figure 1 – Relation between terrain slope and energy cost (after Llobera 2000: fig 2).

Marble (1996) suggests that, since the function relating physiological expenditure to slope is approximately symmetrical, we can safely ignore the whole problem of anisotropy. However, as the graph in Figure 1 shows, the axis of approximate symmetry is at –10% (or -6°) of slope[6]. Consequently, different optimal paths may obtain between two points depending on the direction of travel; hence, the sign of the slope becomes a significant factor in the calculation of friction surfaces and least cost paths.

Krist's approach (above) for calculating a direction adjusted slope map may be combined with the idea of an axis of cost symmetry at -6° of slope, and the formula developed by Pandolf et al. (1977):

$$M = 1.5W + 2.0 (W + L) (L / W)^2 + N (W + L) (1.5V^2 + 0.35V * abs(G + 6))$$

This formula calculates the actual physiological expenditure M (metabolic rate in Watts) involved in moving over natural terrain, and incorporates total weight moved (body W plus load L), velocity V, a terrain factor N describing ease of movement, and percent slope G. I have replaced the final term G in Pandolf's formula by the absolute value of G plus 6 to represent the cost symmetry depicted in Figure 1. Although it is not clear that Pandolf's simple formula represents physiological expenditure as accurately as the more complex functions advocated by McDonald (1961), it at least has the advantage of incorporating the additional factors of load (L) and terrain (N). The terrain factor N is represented by a separate cost surface constructed on the basis of terrain features known to influence movement - marshy areas, roads, and streams of various widths. Marble (1996:5) supplies coefficients for a number of different terrain types, relative to a standard hard but unmetalled surface.

2.3 DISCUSSION

Many of the techniques discussed above, by which costs are calculated, yield *relative* rather than absolute costs; accessibility indices derived from these are therefore also relative. How should this affect our interpretations? I have not come across any cases where absolute (physiological) cost played a direct role; however, relative costs sometimes do have to be 'calibrated' afterward. For example, in order to derive 1 hour catchments for hillfort sites on the island of Hvar, Gaffney and Stancic (1991) were forced to establish experimentally which cumulative costs were equivalent to 1 hour's walk, by logging them at the 1 hour cut-off point in several walks starting at one of these sites.

Llobera (2000:75) wondered how to combine the effect of landscape features (by which he meant archaeological monuments) and 'topographic' (physiological) cost into a cumulative cost calculation. On the surface, this may seem to be a 'technical' question, and Llobera himself hints at potential approaches (2000:81-2), but a more fundamental issue surfaces as well. Whereas measurement and experimentation can establish physiological costs, it is unlikely that 'social' costs can be established with any degree of objectivity. More importantly, it is possible to imagine an endless variety of 'social' cost factors whose effects may overlap, interact, and vary over space and time. The incorporation of social (cognitive) costs into CSA therefore implies that the objective of establishing cost surfaces and paths whose values have intrinsic meaning (for example, expressing travel time or metabolic energy) has been abandoned. It is not at all clear that the values in the new, 'enriched' cost surfaces may even be regarded as relative (ratio scale) measurements, as seems to be suggested in several of the case studies presented in the volume edited by Lock (2000).

Other than trying to agree among ourselves on the actual cost of travelling, are there any other immediate tasks before us? I can see two. The first concerns one of the improvements I suggested in 1992 (Van Leusen 1993), namely the differential weighting of the sites or foci used for cost surface calculations. In a thought experiment, Llobera (2000:74) provided an example of this when he used a monument's 'rank' (the derivation of which was not specified by him) as a multiplier to increase or reduce costs nearby.

The other task concerns improvement of least cost path analysis, one of the more promising areas of development in cost surface analysis. Least cost paths between any pair of points can be generated from cost surfaces in two steps: a cumulative cost surface is generated from the end-point of the pair, which is then 'drained' from the starting point to find the lowest-cost route between the two. Single least cost path calculation has been used by archaeologists on a few occasions, for instance to derive optimum routes between pairs of hillforts in Burgundy (Madry and Rakos 1996:113-117) or between Anasazi communities in New Mexico (Katner 1996). Bi-directional least cost paths and *corridors* (i.e., least cost zones wider than one pixel) were implemented by Krist (2001a,b) in recognition of the fact that many approximate least-cost solutions could have been used in the past.

Compiling multiple least cost paths into a 'least cost network' was suggested early on by Tomlin (1990:170-176 and 212-223) in an application searching for an optimum logging road network and was first archaeologically implemented by Gaffney (pers. comm.) in order to model approaches to Stonehenge; together with Gaffney I calculated similar least cost networks in the late Iron Age and Roman landscape around the town of Wroxeter (Shropshire, UK; this thesis, chapter 16). The first published European implementation is by De Silva and Pizziolo (2001:284-5), who calculate least cost pathways between major Neolithic settlements of the Biferno valley (Italy), and note that secondary settlements are located along these paths. Bell and his colleagues (2002) demonstrate a similar least cost network simulating routes connecting Samnite settlements in central Italy, but refine the implementation by basing it on the calculation of all possible reciprocal pathways.

However, these early examples are still based on relatively simplistic assumptions and coarse data. Route networks are maintained by a range of user groups for a range of purposes: some routes – especially local ones between individual settlements – are used relatively often by a small number of people, whilst other routes are used much less often but by a much larger group of people. The latter tend to form a *dendritic* network originating at the habitual locations of the inhabitants of a region, and converge on a small set of shared resources such as market and cult places. Whilst current approaches concentrate on such dendritic resource-centred networks, little or no attention has yet been paid to the importance of day-to-day social networks by which neighbouring families and villages form and maintain a community. In future models of archaeological landscapes it would make sense to combine resource and social networks.

At a technical level, the accumulation and drainage algorithms used for creating least-cost paths are also far from perfect:

- Even a basic choice such as the selection of the grid resolution for analysis can have a major influence on the outcome of a cost accumulation algorithm, implying that no confidence should be placed in the *precise* line of a 'least cost' path; hence least-cost *corridors* could well present a more realistic approach.

- Cost accumulation is usually performed using either a 4-neighbour or an 8-neighbour filter; even if the latter is used, the 'Knight's Jump' accumulation results in slightly incorrect accumulated costs for most cells. Allowing more directions of movement can further reduce this so-called 'elongation error' of geometric distortion (Harris 2000:121).

- Drainage algorithms, in looking for the lowest neighbouring cell value, cannot reproduce the actual overall least cost path, and in fact are quite likely to deviate significantly from it. Harris (2000:121) mentions several alternative algorithms for calculating optimal routes, and these will have to be evaluated for archaeological use.

Finally, we should carefully examine our model assumptions. Travel rarely if ever happens in a virgin landscape – the landscape has a history of use, which means it is riddled with animal tracks and human infrastructure as established and maintained by the forebears of the current inhabitants. These, in turn, would have had intimate knowledge of this landscape. One could almost assume that, wherever one could wish to go, some sort of path would have already existed! On a less grand note, rather than climbing or descending very steep slopes, people will resort to hairpin bends in order to keep to a comfortable degree of slope[7]. Usually there will be animal tracks to allow this. Thus, surmounting a steep slope (ridge) only requires travelling a greater horizontal distance at a lesser vertical angle.

Most fundamentally and worryingly, a real traveller uses his knowledge of the terrain, the expected length of the trip, the weather forecast, the final and intermediate goals, etc., to decide on the route - a decision that weighs the global costs of alternative routes (cf. Bell and Lock 2000:92). All of the GIS least cost implementations discussed here, in contrast, only make *local* decisions as to which neighbouring cell has the highest or lowest value - they incorporate no *global* knowledge of the landscape at all. This defect can perhaps be turned to good stead if GIS-generated least cost corridors are compared to historic routes: deviations from the 'optimum' route should then indicate the presence of intermediate goals which can be further investigated. In general, more research into such comparisons is indicated, so that we are able to assess precisely *how* far from reality our GIS-generated models still are.

3 LINE-OF-SIGHT ANALYSIS[8]

3.1 PRINCIPLES AND APPLICATIONS

The significance of visibility in the study of archaeological monuments was documented as long ago as the early 18th century, when Stukeley first remarked on the 'false horizon' setting of barrows. Since then, visibility has been an acknowledged factor in the location and construction of archaeological monuments such as hillforts, henges, watch towers as well as barrows, and both intervisibility and viewsheds were formalised, though not yet digital, techniques by the 1970s. Until appropriate digital tools became available in the late 1980s, the laboriousness of having to derive viewshed properties by field observations and manual cartography meant that it never received more than incidental attention. One of the tools that GIS has offered to archaeologists is viewshed analysis. It not only enables researchers to quickly generate and test hypotheses about the (non-) visibility of salient sites and landscape features, but also breathes new life into the study of landscape perception or *cognitive archaeology*.

Single viewshed analysis is now a well-trodden area in archaeological landscape modelling. The basic technique operates on a digital elevation or terrain model (DEM, DTM[9]) to determine which areas are visible from a given three-dimensional location. Single viewsheds indicate whether any two points are intervisible and which area is visible from a particular point; they may also include information about the angle of view. Applications in archaeology range from visual impact analysis for cultural resource management - minimising the visual impact of modern development upon an archaeological landscape (Katsaridis and Tsigouragos 1993, Knoerl and Chittenden 1990, Kvamme 1992) - to reconstructions of Celtic road systems (Madry and Rakos 1996) and explorations of how prehistoric ritual landscapes might have been perceived by contemporary populations (Fisher et al 1997, Ruggles and Medyckyj-Scott 1996, Wheatley 1995, 1996). In further GIS analysis, the basic viewshed can be used to derive properties of the visible areas, relating to such activities as hunting (van Leusen 1993, Krist and Brown 1994), security (Loots et al. 1999, Madry and Rakos 1996), and the confirmation of cultural identity (discussed below). Ruggles et al. (1993, 1996) and Fisher et al. (1997) employed viewshed analysis in the study of bronze age monuments on the island of Mull, western Scotland, extending the idea of visibility to include prominent horizon features and astronomical events. Prehistoric stone rows add the idea of *directionality* to viewshed analysis, possibly aligning with landscape features to 'pinpoint' relevant astronomical locations such as points where the moon rises and sets.

For specific purposes, the concept of viewshed calculation has been refined in order to study *intervisibility* (whether two or more monuments are intervisible and might therefore be part of the same 'system'; e.g., Gaffney & Stancic 1991, Bradley et al. 1993, Ozawa et al. 1995, Bell 1999, Haas and Craemer 1993, Moscatelli 1998) and *visual alignment* (whether two points align in order to visually emphasise or frame a third point; Ruggles et al 1993). Single viewsheds have also been merged to yield multiple viewsheds (Jacobson et al 1994) and added to yield *cumulative* viewsheds (Gaffney et al. 1996b; Wheatley 1995, 1996), both of which will be discussed in more detail below. Finally, the concept of viewshed analysis logically extends to the complement of visibility, the study of *non-visible* areas and monuments. Whereas one particular viewshed will show which areas are hidden from view from a particular vantage point, multiple viewsheds will highlight areas hidden from view from a *class* of monuments, with the potential of having a regional (ritual?) significance. Cumulative viewsheds refine this idea by giving a measure of how hidden particular locations are, enabling us to rank these locations by degree of seclusion. While viewshed exclusion – the deliberate placing of monument or activity so as not to be visible from specific other locations - has figured in archaeological studies, notably Tilley's *Phenomenology of Landscape* (1994), it has only been the subject of one GIS publication in recent years (Lock and Harris 1996:224).

A rather different set of applications arises when viewsheds are used in 'cookie cutters' fashion to derive properties of other data layers in the GIS. Such an approach looks beyond quantitative visibility properties *per se* and asks which objects and terrain features, present within the viewshed, might provide a *reason* for there being a viewshed in the first place. I suggested the example of deriving physiographical properties of the viewsheds of Mesolithic sites in the southern Netherlands, some of which might be camps relating to big game hunting (Van Leusen 1993:118-121). Recently, Wheatley and Gillings (2000: 14-23) have applied the cookie cutter technique in the framework of the so-called 'Higuchi' viewshed properties used in landscape planning. They demonstrated the derivation of the distance-related property of *clarity* (using distance classes based on the visual appearance of standard objects (trees)) and the property of *directionality* based on a calculated aspect layer and 'directionality'.

3.2 METHODOLOGICAL ISSUES

In ascending order of complexity three areas of methodological concern can be distinguished with current viewshed applications – those of realism, of edge effects, and of significance.

Firstly, the issue of realism – is the modelled viewshed sufficiently congruent with the 'real' viewshed to allow archaeological interpretation? In one sense, this is a fairly straightforward technical issue, and a fair amount of GIS literature already comments on the pertinent issues of data quality (especially of the DEM that underlies all viewshed analysis – see the important study by Wood (1996), who also supplies further references), operational assumptions such as the viewing parameters and the use of palaeo-environmental reconstructions (cf. Tschan et al. 2000), and the algorithm employed in the calculation of viewsheds (Fisher 1991, 1992, 1993, 1994; see also Loots et al. 1999; Nackaerts et al. 1999 on the calculation of 'fuzzy' viewsheds). The issue is complicated, however, by theoretical considerations such as the relative merits of employing an 'objective' Cartesian view of geographical space, or of using subjective notions that involve viewer and viewed in a more complex interaction.

Secondly, the issue of edge effects. Since viewsheds are generally large relative to the study region (especially if their radius is unconstrained), they tend to 'fall off the edge' of the region. Conversely, viewsheds of sites lying outside the region would fall partly within the region – but those sites are not part of the analysis so their viewsheds are never calculated! If not properly corrected for, this effect will lead to incorrect multiple and cumulative viewshed calculations, hence to incorrect archaeological interpretations. For example, in a 20 by 20 km study region, calculating viewsheds with a 7 km radius would leave only a 6 by 6 km area in the centre of the study region where the visibility index values are correct; in all areas within 7 km of the edge of the region the cumulative viewshed index (CVI) rises inversely proportional to the distance from that edge (see chapter 16 for a relevant case study).

The edge effect can manifest itself in unexpected ways. For example, Madry and Rakos' (1996) study of the Celtic road network in the Arroux valley in Burgundy suggests that there is a viewshed relation between these roads and the nearby hillforts, and that the intention was to keep the transportation network under constant visual control from these defensive sites. A cumulative hillfort viewshed is calculated and the roads are found to lie largely within the high visibility values. Statistical support for this is obtained by comparing the visibility index of the roads with those of the total study region. However, as no account was taken of the edge effect, the visibility values for the region are incorrect and the conclusion that the roads have a significantly high visibility is unsupported (though it may well be true).

Thirdly, the issue of statistical significance – are the visibility characteristics associated with archaeological remains *significantly* different from background values? Wheatley (1995) discusses one correction that should be standard in all cumulative viewshed operations - the 'view to itself' effect. In the examples discussed by him, this effect entails that the number of barrows observed to occur in a particular viewshed is always one higher than it should be, leading to misinterpretation of statistical results. Even more insidious is the 'viewshed radius effect'; I conducted some simulations (this thesis, chapter 16) that show that the size of the viewshed radius has a profound effect on the distribution of visibility index values across the terrain. For *any* set of points (including archaeological objects), choosing a small viewshed radius will result in a 'preference' for the lower elevations (valley bottoms) occurring in the study area, whereas choosing a large radius will result in a 'preference' for the higher elevations (peaks and ridges). A good example of this effect at work can be found in Lock and Harris (1996: 224, fig 13.5), who note that viewsheds of Neolithic long barrows in the Danebury region are apparently selected so as to 'alert people crossing the surrounding ridgetops'. My work indicates that this 'rim effect' might or might not be entirely due to the choice of viewshed radius.

It is no longer sufficient just to report on the properties of the viewsheds generated for groups of archaeological monuments - archaeological relevance depends on such viewsheds being sufficiently different from the background visibility properties of the study area. For example, viewsheds taken from high points in the landscape will tend to include relatively many other high points - ridges, peaks and such. A sample of viewpoints drawn from such locations (hillforts, barrows) will therefore preferentially 'see itself'. For example, Wheatley (1995, Plate 1) employs cumulative viewshed analysis to study the spatial relationship between barrows in the Stonehenge and Avebury areas. His analysis clearly demonstrates the correlation between viewsheds and landscape morphology, with ridges and peaks being preferentially seen. Wheatley rightly cautions (ibid., 180) against equating such statistical correlation with causation, but does conclude that being able to see other barrows is likely to have been a determining factor for barrow placement in the Stonehenge area.

It is all too easy to employ viewshed analysis simply to support one's preconceived ideas about the cultural and cognitive significance of archaeological monuments, especially if there is little or no methodological control on these quantitative models. Gaffney et al. (1996a:148ff), in their discussion of the viewsheds of monuments in the Kilmartin area of Scotland, fail to convince for this very reason. If, as these authors themselves state, the rock art and standing stones in this area are not visible from more than 100 meters and 3km away respectively, then what is the use of calculating 15km viewsheds?

3.3 VISIBILITY, PERCEPTION, AND THE COGNITIVE LANDSCAPE

It is becoming increasingly clear that archaeologists working with GIS want to be able to escape from the 'objective' geographical space enforced upon them by the design of the software. They want to be able to represent social space - the subjective experience of past people, their perception of their physical and social environment, and their cognitive representation of their world. This is part and parcel of the general cognitive-processual trend in recent theoretical work, a good overview of which can be found in Renfrew and Zubrow's *The Ancient Mind* (1994). Perception and cognition of the landscape are two different concepts, although our perception of the landscape is obviously steered and modified by our cognition (or lack thereof) of its history and constituents.

Perception, as the simple act of being aware of the landscape, has already been to some extent the subject of GIS-study among both geographers and archaeologists. Geographers intend to incorporate qualitative spatial reasoning into formal GIS models (see, for instance, Frank 1996, for a discussion of how reasoning with cardinal directions can be so formalised). Archaeologists have concentrated on less complicated visibility issues involving significant ritual and political landscape features (e.g., Boaz and Uleberg 1995, Nunez et al 1995, Gaffney et al. 1996a, Llobera 1996). Some thought but little action has so far gone into the generation of perceptual variables such as 'enclosedness' vs. openness of the landscape (Llobera, pers. comm.); the potential of such approaches is therefore not yet clear.

Cognitive archaeology in the context of landscape archaeology is the archaeology that concerns itself with the cognitive aspects of past geographical and human landscapes, that is, the perception of significance. According to Zubrow (1994), 'one goal [of cognitive archaeology] is to show that people had preferences independent of economic necessity, and some decisions are independent of utility'. He continues 'as archaeologists, one of our ultimate goals is to extract the cultural ideals from the complicated reality in the complex patterns of prehistoric material remains'.

If we abandon our viewpoint as an external, even extra-spatial, observer of the archaeological landscape as represented by GIS-generated maps, we may instead adopt another role - that of the participant in a cognitive landscape. The link between visibility and cognition has been well made by Gaffney et al. (1996b):

> "A viewshed represents the area in which a location or monument may communicate visual information. Viewsheds may overlap, producing zones in which an observer might be aware of the presence of many such locations, all of which may carry information. The increased density of such information can in some circumstances be interpreted as a measure of the importance of a particular area. It provides a spatial index of perception, mapping the cognitive landscape within which the monuments operated."

Many authors have begun to explore the prehistoric cognitive landscape via visibility in recent years, even though, as Fisher (2000:9) reminds us, 'it is not at all clear how we might compute *modern* cognition in the landscape with GIS' (my emphasis, MvL). For good reasons, such experimental GIS applications tend to concentrate on well-preserved and well-studied ritual landscapes such as the Stonehenge environs, that offer unusually complete data sets and a relatively high a priori degree of certainty that visibility was an important consideration when the monuments in these areas were constructed. These explorations, when visualised appropriately, have the potential of involving us much more closely with the past. Woodward and Yorston (1996) bring the study of landscape perception closer to dynamic Virtual Reality by interactively presenting changes in viewsheds as the viewer moves along the Stonehenge Avenue and different groups of barrows come into view.

3.4 FURTHER WORK

Further work in improving viewshed analysis will need to deal with two issues. The first concerns the technical application of viewsheds; the second, their theoretical justification.

Various technical improvements to viewshed analysis have already been proposed. For example, distance decay functions and 'fuzzy viewsheds' have been used in order to simulate the loss of visual resolution with distance (Fisher 1991, 1992, 1993) and to move from deterministic to probabilistic viewshed models (Fisher 1994, Nackaerts et al. 1999, Loots et al. 1999). Wheatley (1995: 181-2) includes a useful discussion of error and uncertainty in viewshed maps. Others (Ruggles and Medyckyj-Scott 1996) have applied a correction for earth curvature that is particularly relevant for the modelling of astronomical observations[10]. Further improvements follow from the discussion of methodological problems above. The preliminary visibility significance tests I conducted indicate that statistical control of viewshed analysis needs to be much stronger before any archaeological interpretations can be built upon it. The tests will have to be generalised so that reproducible results can be obtained from them, and a proper way of incorporating background visibility data into viewshed analysis has been found. One way forward might be by resorting to *relative* visibility measures – for example, Lock and Harris (1996:232 and fig 13.15) note that early Iron Age hillforts in the Danebury area are positioned to maximise visual dominance over adjacent valleys and surrounding farmsteads *at the cost of* all-round defensive visibility. I am less happy with the tack taken by Gillings (1999) and Woodward and Yorston (1996). Gillings looks to Virtual Reality visualisations in order to explore the significance of archaeological viewsheds; Woodward and Yorston have implemented an application similar in spirit, that uses Java software to create interactive maps of the barrows in the Stonehenge area, where barrows visible from the current position of the mouse cursor light up. Although this type of work certainly comes closer to the post-processualist ideal of being participant in, rather than an observer of, the archaeological landscape, I am worried by what must be an increasing temptation to throw technical rigour to the wind.

Justifying viewshed analysis on a theoretical level is equally as important as its technically competent implementation. How important is it in fact to be able to see directly a particular site, monument, or social activity, as opposed to knowing or being aware of its presence and location? Smoke and fires, the latter especially after dusk, must surely rate among the most visible phenomena even from a great distance, and it is not at all necessary to be able to see the *source* of the smoke and fire to be aware of what is going on.

And of course there is no reason to limit ourselves to vision: things heard or smelled might be as significant as things seen – the Neolithic barrows of the English chalklands, when first constructed, would have been highly visible, but their visibility must have dropped as they gradually became overgrown with moss, lichen, and grass. Could it be that the less permanent features of a barrow cemetery were in fact the most visible (totem poles), audible (wind chimes), or smellable (decomposing offerings?). The first hints of research turning in this direction are now detectable: classical farmsteads in the countryside surrounding the ancient Greek city of Hyettos are thought to take 'advantage of the unique acoustic effects of the basin 'auditorium' surrounding the acropolis and lower city, enabling them to partake aurally as well as visually in the activities taking place' (Gillings 2000:115; Gillings refers to the modelling of such perceptions as 'sensuous' GIS).

Following this line of reasoning to its logical conclusion, one might even question whether the cognitive landscape is not constituted as much by 'unsensed' presences as it is of the more direct sensed kind. Inspiration for such thinking will no doubt be found in the ethnographic literature, but there is also the danger of over-interpretation – *anything* in the landscape could have had cognitive significance. That does not mean to say that it had.

4 CONCLUSIONS

INCREASED REALISM

It is evident that, a decade after the first LOSA / CSA studies were conducted, an initial phase characterised by naïve applications and constrained by the capabilities of generic GIS has drawn to an end. It is currently being replaced by a phase in which specific procedures are being proposed in order to implement ever more realistic models of human perception of the landscape.

Although opinions about how to improve studies based on viewshed and cost surface techniques are divided, all are agreed that they can and should be improved. On the one hand, exploration of refinements to the 'environmental' approach current throughout the past decade continues - see, for example, the experimentation with the inclusion of a variable representing seasonally changing vegetation in the Polish Mesolithic in viewshed studies by Tschan et al. (2000). On the other hand, proponents of the 'enrichment' approach are particularly vocal regarding methodological improvement, which they see coming mainly from the field of landscape analysis. Baldwin et al. (1996) provide a very useful review of actual and potential approaches to modelling environmental cognition through line-of-sight analysis in GIS from the perspective of landscape analysts. They divide personal experience of the landscape into four categories - physiographical characteristics, the presence of specific physical features, cognitive variables, and viewer interest, and conclude that deterministic analysis in GIS can become more accurate by adopting a flexible approach to cognitive criteria. Early explorations of such an approach are Wheatley and Gillings' (2000) investigations in the framework of Higuchi viewshed properties, and Llobera's (2000) implementation of 'attractive' and 'repellent' features in the landscape.

However, fundamental limitations to the use of GIS in such landscape studies have already come in sight, causing Lock (2000:60-62) to predict that refining current approaches will continue to produce inadequate models because they continue to represent meaning as attributes of the landscape rather than as properties of the people in it. Such a fundamental shift in emphasis suggests that future models should take the form of artificial societies built by programs representing individual humans, their intentions and reactions to external stimuli (cf. Llobera 2000:81-2). This new phase is likely to be dominated by a much more limited number of researchers who have access to the specialist software tools needed for this type of landscape analysis.

TESTING & VALIDATION, OR EXPLORATION?

The apparent conflict between adherents of processualist and post-processualist approaches has been shown to be beside the point from a pragmatic point of view. The practical differences between studies presented so far by either side appear to be small, and a much more significant watershed is likely to separate studies that fail to adduce proper supporting evidence to their interpretations, from those that do. Whilst naïve processualist approaches have since long rightly been criticised for failing to address pragmatic and procedural shortcomings (most recently in Wheatley & Gillings 2000: 5-14), having a post-structuralist outlook in itself does not help to establish procedural rigour. Both Fisher (1999:9-10) and Llobera (2000:66) note the lack of validation or even methodology accompanying post-processual works.

A general point that emerges is the lack of supporting evidence given for claims of unusual cost or viewshed properties for particular locations within a region. Fisher (1999:8) is not the only one who has noted that most 'contextual' studies do not attempt spatio-statistical analysis, and therefore lack proof for their inferences. Yet tests can be carried out to demonstrate that the results obtained are unlikely to have arisen by chance, as is shown by Fisher and others (1997), who employ Monte Carlo testing of their hypotheses.

The general approach advocated to substantiate LOSA and CSA results obtained for a sample of archaeologically meaningful locations is to compare them with one large or many similar-sized samples of random chosen locations (cf. Wheatley 1995). This is typically done by generating a cumulative visibility index (CVI; see, for example, Lake et al 1998:36-38, Bell & Lock 2000: 96-98) or a cumulative accessibility index (CAI; for example, Llobera 2000: 70ff) for all or a representative subset of locations within the study region. The result obtained for the sample of interest can then be formally compared to the population (one-sample tests) or to a representative sample of it (two-sample tests).

Lake et al. (1998), investigating whether the viewshed sizes (areas) of Mesolithic sites on the island of Islay off the Scottish west coast were significantly different from those of non-sites, used a two-sample significance test of sites against a 5% random sample of locations and found that their hypothesis was not supported by the evidence.

Another method by which LOSA- or CSA-based models may be supported is by comparison with independent archaeological evidence. For example, networks of least-cost paths may be compared to historically known networks such as the mule-paths that criss-crossed the Italian highlands until recently. If this approach is taken, circular arguments are to be avoided: in some cases, models have been ‘tweaked’ until they fit the evidence, after which the fit is taken as evidence for the correctness of the model. For example, the optimal path calculated by Bell and Lock (2000) adheres to the known route of the Ridgeway not only because of the constraints imposed by the distinctive landform of the region (as noted by Harris 2000:119), but also because the authors adjusted several parameters in the cost calculation in order to *force* the optimal path into resembling the route of the Ridgeway. Clearly, in such a case the resemblance between the two paths cannot be taken to be supporting evidence for the correctness of the calculation.

PROCEED WITH CAUTION

This paper critically examines the logic of assigning cognitive significance on the basis of multiple or cumulative visibility and accessibility indices, and finds that insufficient attention has been paid to some important methodological aspects of spatial analysis – most notably the need to calculate ‘background’ or ‘potential’ indices against which an actual outcome may be judged. Recent work points to least cost path analysis as the most profitable avenue for further research in cost surface analysis. There are at least two avenues for further work here; firstly, analysis of historic infrastructural networks which may serve to ‘calibrate’ data-independent models; and secondly, vector analysis of networks constructed through raster-based cost surface analysis. Recent viewshed applications seem to concentrate on studying the (inter-) visibility of ritual monuments, but as has been made clear here will need to apply a lot more rigour to their technical execution.

Two specific approaches have been suggested: firstly, since there are a large number of potential sources of error, it is deemed unwise to believe the outcome of any particular LOSA or CSA. As Wheatley and Gillings (2000:5) suggest, we should instead study the trends emerging from an accumulation of such single outcomes. Secondly, rather than attempting to interpret the viewshed or accessibility properties of sites directly, we should study the *differences* between sites and between sites and ‘background’. These approaches express a probabilistic view of modelling - one where models are used to indicate only how *probable* it is that certain activities take place in certain places.

Rather than continuing a fruitless processual / post-processual debate, this paper shows current GIS implementations of ‘cognitive’ landscapes to be little more than a semantic change of clothes. The post-processualist argument has mostly taken the form of a bashing of supposedly ‘data-led’, ‘environmentally determinist’, and ‘naïve’ applications copying the worst of New Archaeology practices. However, applications billing themselves as ‘cognitive archaeology’ seem to boil down to the same combinations of viewshed and cost surface analysis explored by others as well. It is also possible to argue that cost surface and viewshed calculations are themselves deterministic methods. Llobera’s (1996) study of the visibility of late prehistoric ditches in the Wessex chalklands, although couched in a theoretical context rather different from that of systems theory and processualism, still attempts to derive cognitive aspects of late Bronze Age society (the awareness of being inside a territory) in a deterministic manner - the location of the ditches is fixed, the calculation of their visibility is based purely on properties of the elevation model. So the difference with what has been termed environmental determinism is in the *environmental*, not the determinism, and we might as well speak of *cognitive determinism* when describing such work.

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[1] For an accessible review of the underlying theory and method of site catchment analysis, see Roper 1978. For a brief discussion of spatial allocation, territoriality, and cost surfaces in a GIS context, see Kvamme 1999:174-176.

[2] For a GIS re-analysis of the same data, see Kvamme 1992.

[3] Part of the following is reproduced from an e-mail sent by Mark Gillings to the GISARCH mailing list (Gillings, Fri. 10 Oct 1997).

[4] Regrettably, insufficient details were published to allow a proper evaluation of this method.

[5] For those who would like to experiment with alternative cost models, I reproduce these functions here. V is speed, G is the adjusted slope value. For slopes from –40 to –20 degrees, McDonald (1961) calculates energy expenditure F as follows:

$F_1 = 0.000049V^2 - 0.00415V - 0.13276G - 0.004692G^2 - 0.00005213G^3 - 0.0003257VG + 0.000002036V^2G - 0.8588$. For slopes from –20 to +5 degrees, the function becomes:

$F_2 = 0.00202V + 0.000021V^2 + 0.0256G + 0.00154G^2 + 0.000044VG - 0.00000314V^2G + 0.3515$. For slopes from +5 to maximum, slope S must be entered in degrees instead of percent, and the function becomes:

$F_3 = V * (0.00275 + 0.049\sin(S)) * \cos(S) + V^2 * (0.00002 - 0.00033\sin(S)) * (\cos(S))^2 + 0.396 + 0.17\sin(S)$.

After merging of the map layers generated by the functions F_1-F_3, and adjustment for pixel size, a 'topographic' cost surface in kcal results.

[6] This physiological function was apparently derived by Llobera (2000: 71, Figure 2) from multiple sources: Margaria 1938, Kamon 1970, Minetti et al. 1993, and Minetti 1995.

[7] Thus, the cost of ascending a very steep slope to a specific height could be approximated by dividing that steep angle by some acceptable angle of ascent – say, 15° – and using the outcome as a multiplier for the *horizontal* costs. For example, the cost of climbing a 45° slope over a horizontal distance of 200m (i.e., to a height of 200m) is equivalent to 45 / 15 = 3 times the cost of 200m horizontal travelling.

[8] Since the calculation of a line of sight between a pair of points is the 'primitive' operation underlying all viewshed-related analysis, I have thought it proper to use this term rather than the more widespread 'viewshed analysis'.

[9] Although much of the literature treats these two terms as interchangeable, there is an important technical distinction between them – a DTM contains information about terrain features such as ridgelines, breaks in slope, etc., while a DEM is a simple rectangular lattice of elevation values.

[10] The correction for earth curvature applied to DEM data is: $d^2 / 1.273 * 10^7$, where d is the horizontal distance in meters to any point in the study area. A point at 10 km distance would thus be set nearly 8 metres lower, influencing the viewshed coverage.