A Submission presented in partial fulfillment of the requirements of the University of Glamorgan / Prifysgol Morgannwg for the Degree of

Doctor of Philosophy

Visual Topology in SDI: A Data Structure for Modelling Landscape Perception

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This research program was carried out in collaboration with The James Hutton Institute and Supported by the Macaulay Development Trust

September 2011

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Certificate of Research

This is to certify that, except where specific reference is made, the work described in this thesis is the result of the candidate's research. Neither this thesis, nor any part of it, has been presented, or is currently submitted, in candidature for any degree at any other University.

Signed ......Neil Sang......

Candidate

Date 26/09/2011......

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i) Abstract

Visual Topology is a used here to describe the spatial relations between objects as they appear in the 2D viewing plane. This thesis sets out the concept, explains why it is needed in Geographic Information Science and suggests how it may be computed through development of prototype software.

Section 1 considers the functionality that any Spatial Data Infrastructure would need to encompass in order to support the inclusion of visual analysis into landscape planning and monitoring systems. Section 2 introduces various aspects of visual topology. In particular it sets out how visual intersections of occluding edges may be modelled topologically and formally defines a novel higher level topological structure to the *viewing* space – the 'Euler Zone' based on the Euler complexity of a graph formed by the occluding horizons in a view. Whether such a graph has meaning to an observer is considered in Section 5, which presents the results of a web based forced-choice experiment with significant implications for the role of topology in modelling landscape preference via quantitative metrics derived from 2D maps.

Sections 3 and 4 discuss how existing methods for handling perspective models and visualisations need to be improved in order to model visual topology. Section 3 focuses on the limitations of current techniques and design criterion for a new methodology. Section 4 looks at the lessons learnt from developing a prototype implementation (VM-LITE) based on Quad-Edge Delaunay Triangulation, in the VoronoiMagic software package.

Some potential applications are highlighted, both within landscape modelling and beyond, before drawing conclusions as to the potential for the concepts and methods respectively. Although important research questions remain, particularly as regards view point dynamics, Visual Topology has the potential to fundamentally change how visual modelling is undertaken in GIS. It allows the analysis of scenes based upon a richer representation of individual experience. It provides the basis for data structures that can support the extraction of generalisable metrics from this rich scene information, taking into account the qualitatively different nature of scene topology as distinct from metrics of shape and colour. In addition new metrics based on attributes only apparent in perspective, such as landform, can be analysed. Finally, it also provides a rationale for reporting units for landscapes with some measure of homogeneity and scale-independence in their scenic properties.

Keywords: Visual, Topology, GIS, SDI, Voronoi, Data Structure, Landscape metric, Planning.

ii) About this thesis

Conventions

Quotations : Direct quotations are given in double inverted commas. Single inverted commas, unless a sub-quotation, are used to introduce new terms, recognise other's terminology is being refered to out of context or to imply a colloquialism or other '*sic*'.

Contributions

VoronoiMagic was developed by Professor Chris Gold, Dr. Maciej Dakowicz and others.

The terrain data visualized in figures 14, 21 and 22 was developed by Pernette Messager.

The landscape models shown in Figure 21were developed by Dr Åsa Ode Sang and Professor David Miller as part of the VisuLands Project (Ode, Tveit et al. 2008).

Dr. Luis Isquierdo helped improve the topological notations.

Alec Tunbridge helped with the development of the internet survey software.

Professor Abbas Rajabifard provided permission for reproduction of artwork in figures 1, 3 and 42.

The survey undertaken for Section 5, was developed in consultation with Professor Caroline Hägerhäll and Dr Åsa Ode Sang. They provided advice as to choice of image and discussed my interpretation of the results. The survey implementation, the writing of chapter 5, and the conclusions drawn are entirely my own responsibility.

Acknowledgements

My sincere gratitude is given to the following people who supported me in my studies:

Professor David Miller, Professor Christopher Gold, Dr. Maciej Dakowicz, Professor Caroline Hägerhäll, Dr Matt Aitkenhead, Pat Bayley, Vivienne King, Alec Tunbridge, Deborah Slater, Dr Elizabeth Duff, Dr. Stewart Rhind, Professor Richard Birnie, Pernette Messager, Dr. Luis Isquierdo, Rosemary Sang, William Sang. Dr Åsa Ode Sang.

This work was funded by and undertaken at The Macaulay Institute (now The James Hutton Institute) Aberdeen under the supervision of Professor Gold (University of Glamorgan) and Professor David Miller (The James Hutton Institute). It also benefited hugely from a one year sabbatical at Alnarp, the Swedish Agricultural University (SLU).

The idea for this research first arose over many tea-break discussions at the Macaulay Institute with Åsa Ode, then a visiting PhD student, about her doctoral research into landscape preference. I could not have imagined at that time how fruitful those discussions would prove to be. My heart felt thanks to Dr. Åsa Ode-Sang for all her inspiration, encouragement, patience and support since!

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Visual topology in SDI: A data structure for modelling landscape perception

vi) Introduction

Visual Topology is used here to describe the spatial relations between objects (or parts of the same object) as they appear in the 2D viewing plane. This thesis sets out the concept, explains why it is needed in Geographic Information Science to meet the growing demand for objective analysis of human visual experience at the landscape scale and suggests, through development of prototype software, how it may be computed.

The argument set out in this thesis is that Visual Topology is relevant at all stages of geo-information processing pertaining to visual perception. Data collection, be that one-off or long term landscape monitoring, may use Visual Topology to ensure that visual prominence is represented rather than only the spatial extent of the views onto features. It can help in the definition of spatial units on land cover maps in order to minimize the Modifiable Areal Unit effects of visual occlusion that arise with visualisation and view-analysis processes. It is also fundamental to developing efficient data-structures for mapping and analysing perspective views and it may be an object of interest in itself, describing a distinct aspect of visual character. Whether this is successfully demonstrated may be considered with respect to whether null hypotheses postulating the opposing view are disproven:

Null 1-No spatial base unit exists that can be objectively defined by a visual landscape metric and is stable under local view-point change.

Null 2- Apparent topological complexity is not associated with viewer perceptions of landscape.

Null 3 - Visual Topology does not: (a) reduce storage requirements for results of visibility analysis compared to a traditional raster view-shed; (b) allow faster querying of a changing view than existing standard GIS methods; (c) allow information about a view (in terms of its geometry and topology) to be queried directly from Digital Elevation Models beyond that available by standard GIS methods.

No concept disproving these null hypotheses has been found to be represented in any SDI or standard Geographic Information System (GIS), nor, as will be argued from the literature, are visual aspects generally considered part of the role of topology in spatial theory. This poses the research question of whether a data structure can be designed which enables the analysis of visual topology? If so, can such a structure be incorporated as a future requirement of Spatial Data Infrastructures? To the author's knowledge, this thesis represents the first exploration of 'visual topology' to that end. As such it has required a balance between breadth and depth in order to both explore sufficient territory in this new area to demonstrate its utility, whilst also providing a legible road map from need through theoretical development and data structure design to implementation. It is worth highlighting the three main stages along this route:

1. Visual Landscape SDI – Establishing that a visual component within a landscape SDI would be of value and that a model of visually apparent topological relationships is important to provide an appropriate spatial base to this. (Section 1).
2. Visual Topology – Defining what visual topology is and its role in perception. (Sections 2 and 5 respectively).
3. Data Structures and Processing – Why a new data-structure is needed to facilitate richer visual query of landscape and how this can be implemented (Sections 3 and 4 respectively).

Each of these areas consists of a wealth of previous work upon which the ideas and methods developed here rest. To retain the link between the review and the topic of the section, this literature is reviewed within Sections 1, 2, 3 and 5 respectively as the discussion develops. In Section 1 this pertains to both the theory of SDI development and to landscape planning mechanisms such as Environmental Impact Assessment.

Section 2 spans literature from GIS, computer vision and topology, and also includes environmental psychology and landscape architecture. Section 3 considers methods for visual processing in the GIS and computer graphics traditions, and the reasons for their continuing separation as well as the related issue of alternative data structures for terrain representation. Section 4 contains relatively few references to the literature as the key design issues are discussed in Section 3, thus references are only used to support and further inform on particular implementation decisions. Section 5 focuses primarily on environmental psychology and landscape preference modelling literature. Much could be added to any one of these areas, but it is hoped that sufficient depth has been achieved where needed to give confidence as to the novelty and relevance of the theoretical development and competence of the software design and implementation. Similarly, discussion of each component is provided at the end of each section, from which conclusions have been drawn in Section 6.

Section 1 considers the functionality that any Spatial Data Infrastructure would need to encompass in order to support various levels of the planning system with information about the visual landscape. This serves as the core end-use criterion for subsequent sections developing the theoretical ideas and software functionality needed to feed into planning processes.

Section 2 - Introduces various aspects of visual topology, including formal definitions of a novel topological structure to the viewing space – the 'Euler Zone'. It begins with the idea that apparent adjacency may be modelled as a topological link across space (along the line of sight). This may be stable to incremental viewpoint change provided that change does not alter which edge in a dataset occludes which other edge. Since horizons mediate occlusion and occlusion mediates the non-linear effects of view point change, it is posited that other effects of perspective so troubling to landscape metrics (e.g. variance in shape and scale) can be modelled statistically within the limits of a stable visual topology.

A series of occluding horizons seen in perspective may also be considered as a 2D graph in the view plane. Edges of this graph function to mediate 'lateral' visual topology, i.e. what lies adjacent in the view such as the potential for visual contrast, but also depth of view and the 'mystery' as to what might be occluded. Graphs have their own graph-topology, for which a general index of complexity, the Euler Character, may be calculated. This gives a higher level measure of topological complexity which may be stable under detailed topological change and under changes in scale and resolution. It therefore presents the possibility of developing a landscape metric which not only measures a distinct aspect of human perception so far largely ignored in landscape preference theory but which is also stable with respect to local viewpoint change.

Having formally described Visual Topology and established that it is significant for people's perception of landscape, attention is turned to how it may be computed. Section 3 reviews existing methods of handling visual queries both in the GIS tradition and that from computer graphics, before setting out the necessary developments required to support the planning process set out in Section 1 and the reasons for implementing this within a Quad-Edge Delaunay Triangular Irregular Network.

Section 4 discusses the implementation of VM-LITE (VoronoiMagic Landscape Information Tessellated Environment) in detail. The new code itself stretches to over 6000 thousand lines[1] so is not reproduced in hard copy. Numbered references to the relevant places in the code (prefixed by '#') provide the possibility to review each part of the software step by step via the pseudo code in Appendix 1 and to find the relevant section in the code extracts in Appendix 2 (a copy of the program may be provided on request and subject to appropriate license agreement). This section finishes with lessons learned from the experience of implementing the design. Pragmatic compromises are acknowledged and potential improvements explained. Some fundamental issues, such as the problem of small number computation, are also highlighted since these would confront any such implementation.

Section 5 reports an investigation into whether the Euler Character of a horizon graph is significant for how people perceive a landscape. The study consists of an internet based survey where by people presented with a pair of images selected the one they found "most interesting". Images were controlled to ensure they were generally similar except for the Euler character of their respective horizons. Results are then

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[1]Core classes to the 'LITE' component only, including comments and test code..

analysed via graphing and Restricted Maximum Likelihood (REML) to establish if the variance in Euler Character explains any differences in the rate of image selection.

In terms of the balance of the thesis between the broad SDI goals, specific theoretical development and implementation, it may be helpful to consider how it relates to the general model of SDI put forward by Rajabifard et al. (2002) and considered further in Section 1.

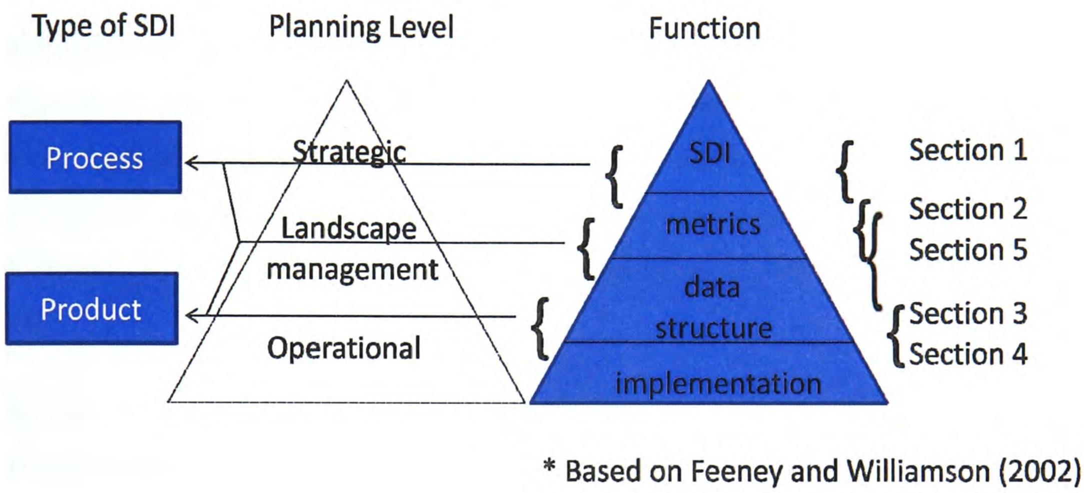

Figure 1: Relationship of thesis to theory of SDI structure in Rajabifard et al., 2002

Figure 1 relates the thesis Sections to the relevant level in Rajabifard et al.'s (2002) SDI pyramid. Sections 3 and 4 undoubtedly constitute the bulk of the work and form the practical foundation upon which a range of applied products useful in landscape planning and beyond might be built. Section 5 represents one such potential product, in providing a landscape metric relevant to modelling what it is people find interesting in landscapes. Such a metric could be useful in specific planning problems, but also feed upwards to uses in strategic landscape management and monitoring. After setting out key theoretical ideas of Visual Topology, Section 2 takes the same metric as the stage below but with the ambition of using it to define landscape monitoring units as called for in Section 1. Although the flow of information is upward, the criterion for that information stem from the top down, such that a practical need demands new theory and new methods to inform the development of that theory. Techniques are selected accordingly and not, as the aphorism goes, the 'answer for which a problem is sought'. This is also very much the order in which research developed, and so it is proposed as the most helpful order in which to present the work, but sub-groupings of Sections may be read as relatively self-contained work as indicated by the parentheses on the left hand side of the pyramid. For this reason, and because the reader is likely to be introduced to at least one or more new fields of knowledge, key points are occasionally returned to in each Section to refresh the reader's memory or add detail which may have been confusing to include elsewhere. The work is sectioned such that the thread of the argument may be easily picked up further on. Thus Section 3 (Section 3.5-3.7) provides the key methodology for the software without the distraction of specific implementation issues which are left to Section 4. Similarly, Appendix 1 provides the gist of each stage of the software explained in plain English, while Appendix 2 provides the actual code. Both of these Appendices are referenced in Section 4 via numbers (e.g. '#20.2') so the reader may consult either if more detail is desired, and read the general argument uninterrupted by tracts of computer code if not.

Section 6 draws the various strands together to consider how the practical implementation of software to model Visual Topology may facilitate (or restrict) its application in the various stages of landscape planning. Some potential applications are highlighted, both within landscape planning and beyond, before drawing conclusions as to the wider potential for the concepts and methods. Although important research questions remain, particularly as regards viewpoint dynamics, Visual Topology has the potential to fundamentally change how visual modelling is undertaken in GIS. It allows scene analysis based on a richer representation of visual perception, which is a fundamentally individual experience. It provides the basis for data structures that can generate metrics from this rich scene information, including taking into account the qualitatively different nature of scene topology. Finally, it also provides a rationale for landscape reporting units with some measure of homogeneity and scale-independence in their scenic properties.

1 Section 1 - The requirements for an SDI to support visual landscape analysis for Environmental Impact Assessment.

1.1 Introduction

This section sets out some key informational problems facing any attempt to balance the various needs of society to use and develop land, with the fact that landscape is "an important part of the quality of life for people everywhere" (Council of Europe 2000 preamble) - the Environmental Impact Assessment being an important policy mechanism to that end (EEC 1985). Firstly it considers the need to address the significance of the Modifiable Areal Unit Problem (MAUP) as a driver of Spatial Data Infrastructure (SDI) development, and whether it has received sufficient attention - particularly as SDI have the ambition to bring spatial data to a wider audience who will be largely unaware of the problem. It considers how the visual presentation of data generates MAUP in a particularly challenging way, and the significance of this for Environmental Impact Assessments (EIAs). Finally it argues that mitigation of MAUP due to visual representation needs should be part of the design of any SDI to support EIAs.

1.2 SDI and the Modifiable Areal Unit Problem

Moran et al. (2003 p. 62) describe the selection of an appropriate unit of analysis as the "greatest challenge to theory in human ecology". It is a challenge which must be undertaken if an understanding of processes at the landscape scale is to be achieved since, by definition, landscapes are formed by the interaction of human and natural processes. Unfortunately information on the component parts of such processes is often not available in the same units (Sang, Birnie et al. 2005) and even where a common spatial base exists such as that for the U.S. Census Bureau's TIGER data (www.census.gov/geo/www/tiger/) the analytical suitability of this is subject to the operational drivers of that base (Sang, Birnie et al. 2005) which may not be appropriate to the intended use. Attempting to analyse relationships by disparate units, or fit two datasets to a common unit, introduces errors of scale and displacement collectively known as the Modifiable Areal Unit Problem (MAUP, see

(Openshaw 1984. ; Sang, Birnie et al. 2005)) which is well understood in theory but hard to deal with in practice (Huby, Owen et al. 2007; Huby, Cinderby et al. 2009).There are a number of reasons behind efforts to develop Spatial Data Infrastructures (Williamson, Rajabifard et al. 2003), such as data format interoperability, standardisation of search protocols and democratisation of spatial data access. These share the same fundamental requirement, that datasets are appropriate and technically (if not practically) available for re-use in as wide a range of applications as possible.

Once found, acquired and converted to the required formats, the utility of data is still fundamentally constrained by its collection methods and units. SDI development has been particularly driven by policies which require a more holistic evaluation of environmental management plans (Council of Europe 2000; Craglia and Annoni 2003), meaning multiple data sources must be sufficiently comparable as regards method and units to provide robust information about how their respective phenomena relate – making MAUP a central issue in SDI design. Recent work on SDI has extended the concept to take into account the processes for which data are required to support (Masser, Rajabifard et al. 2008). For example, a raster map of water levels over a DEM might be a reasonable representation of the situation at a given time, but the resolution could be too coarse to run a robust flow model because small local errors can accumulate down-stream. In this case, the issue of MAUP becomes particularly significant as not only might the units of data collection not fit the units of analysis, but the processes concerned often extend beyond conventional GIS analyses to non-GI professionals who may not appreciate the potential problems. Legislation such as INSPIRE[2] (EU 2007) recognises the importance of democratic access to information. INSPIRE sets a context for the provision of access to information and the development of more intuitive means for its presentation to those without cartographic training.

1.3 The EIA and MAUP

The visual characteristics of a landscape are some of the most widely experienced yet difficult, and controversial to define (Walker 1995). The European Landscape Convention (Council of Europe 2000) has led to the need for an 'objective' assessment of these values and the potential impact of changes to them. This raises two problems. The first is to define

[2] Infrastructure for Spatial Information in the European Community

‘objective’ in a way which most people would agree with and few disagree, which entails finding ‘representative’ examples of the various values. The second is therefore to define spatially where various landscapes are, and concomitantly from where there is a ‘representative’ view of them. Both the scale and displacement problems of MAUP occur when one attempts to model the visual characteristics from a particular point with data available on a map. Perspective influences the scale at which different parts of the map data is seen, and landform can mask parts of the data (Germino, Reiners et al. 2001). It could be, for example, that a polygon on the map is classed as heather, but the segment of the polygon actually visible in the view is predominantly rough grassland. This is a particularly challenging context as the units of analysis may change with changes in visual perspective. In addition, human-ecological landscape value is not simply a function of the landscape features which are visible, their pattern (Olsen, Dale et al. 2007) and their arrangement in the view also appears to affect people’s preferences (Palmer 2004).

Perspective also introduces problems of boundary and scale dependency at the landscape level (through limiting any simultaneous view to a subset of the total area). Characteristics of this landscape level unit, in landscape planning parlance the ‘sites’ and ‘regions’ (Marsh 2005), such as connectivity and pattern, can be seen therefore as attributes similarly subject to MAUP. This has important implications in Environmental Impact Assessment (EIA) (EC 1997) where setting the outer bound to the study area and basic units of analysis there-in may determine the variety of impacts and options considered (Karstens, Bots et al. 2007). Integrating data and models with visual analysis therefore represents a sub-section of the wider data integration problems faced by Spatial Data Infrastructures (SDIs). It provides a demanding context in which to test solutions to the generic problems of data-data integration (i.e. landcover and DTM), and data-process integration (i.e. applying maps to visualisations).

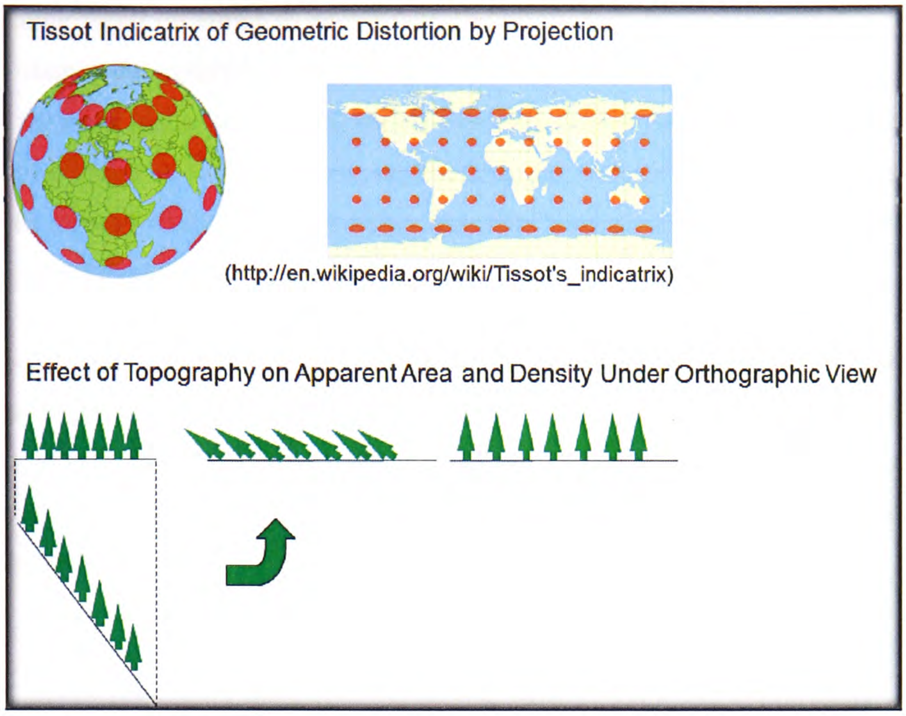

Figure 2 : MAUP due to perspective and area selection

The problem of how perspective impacts on spatial units, and statistics related to those spatial units, is not new. As Figure 2 illustrates, the age old problem of map projection is an example of how maps distort the reality on the ground. Not only are all projections drawn from a particular perspective (albeit a theoretical one), but surveying and ground-truthing relies on obtaining a limited number of perspective views onto the mapped area. However, reversing the process to include map derived visual metrics and visualisations in the planning process brings the issue closer to the end users who may not understand the potential problems. Take the example of tree density in Figure 2, when applying a model of visual attenuation due to ground cover in different seasons (for a visualisation of a windfarm for example), should the same attenuation per meter be assumed for all map polygons classified as woodland regardless of their slope and the angle of view? Consideration of such factors can significantly influence the quality of the outcome of analysis of visibility of features, and has a role to play in designing 3D visualisations.

1.4 The EIA and SDI

Visual landscape analysis, particularly within a participatory planning context, poses a significant theoretical and computational challenge. In order to provide objective stimuli, one must identify from the infinite range of possible locations, viewing angles and focal lengths representative views on which to base public consultation or metrics for visual quality. Thus however simple the criterion, many perspective analytical operations would be needed to establish the norm and to find representative examples. Theoretically there are many possible landscape variables to consider in a stratification, as well as overarching issues such as whether to attempt to factor in the likely attention level each variable might attract from observers and the relative weighting with respect to viewing distance.

Alternatively, one could develop the ability to analyse responses during directed or free movement through a landscape, be that real or virtual such that the stakeholders themselves select the amount and distribution of information. Ideally this would be in an efficient manner which would allow modelling to include stakeholder interaction, not just post-processing of passive responses.

For both sampled views and free-movement models one needs to address the dual problems of hidden surface removal (HSR) and shadow casting (Sammet 1990), as these determine what parts of a dataset appear where in the perspective view. HSR remains a computationally 'hard' problem even given recent advances in graphics processing (Leubke, Reddy et al. 2002) so most applications such as computer gaming, will choose to simplify the data. For example, a game's story may pre-define the available routes taken and it may use simpler geometry for game play than the picture rendered on the screen (see 'gaming optimisations' (Leubke, Reddy et al. 2002 pp. 174-183). In a landscape analysis context however, it is necessary to provide free navigation by stakeholders to avoid biasing the impressions gained from interpretation of the model. Landscape analysis also requires precise analysis of the images which stakeholders see and react to, so the underlying model must be complete and similar (geometrically) to the rendered image.

The technical problems (and possible solutions) to analysing perspective landscape data are explored in Section 3. However it is important to note that, despite the improvements in computer graphics, technological advancement alone will not remove the need for an SDI solution to the problem of perspective analysis of landscape data. Analysing perspective information is only useful if the perspective view is feasible to build and if the visualisation is scientifically robust i.e. sufficiently close to what is likely to be experienced but no closer than can be objectively justified (Sheppard 2001; Appleton and Lovett 2003). Building scenarios of future plans entails combing multiple spatial datasets, therefore also combining their inaccuracies and incompatibilities. These sources of uncertainty may be given focus by any particular perspective view which may not be picked up by standard measures of accuracy and compatibility such as Root Mean Squared Difference. A common, and so usually accepted, example of this is the blocky appearance of grid data in the foreground of visualisations, but issues such as the effect of inter-dataset unit heterogeneity at foreground scales is less well understood, and much less intuitive.

If an SDI for EIA is to be widely adopted then it needs to be compatible with broader moves in SDI development. Given the application context, it must also consider issues of utility within landscape research and planning and establish what existing solutions may already exist for analysing perspective information. The following section therefore takes an overview of current trends in SDI. Thereafter, an overview of landscape planning and methods in landscape research is presented in terms of how this fits with models of SDI development. Finally, some key research issues are identified as necessary to bridge the gap between how people see landscape (i.e. viewed in perspective), and the largely cartographic paradigm of planning processes (Appleton, Lovett et al. 2002; Paar 2006).

1.5 Spatial Data Infrastructures

1.5.1 Current trends

'Spatial Data Infrastructures' (SDI) are still relatively novel as a research topic, Masser (2005) provides a brief history and state of play by region which remains reasonably current in theoretical terms, though some practical implementations have progressed substantially, not the least of which being INSPIRE. Like many early GIS texts (Maguire, Goodchild et al. 1991; Burrough and McDonnell 1998; Longley, Goodchild et al. 1999) current SDI texts devote considerable effort to defining SDI, so a review of SDI risks becoming a thesaurus of alternative definitions of what an SDI is i.e. a compendium of various technical and organisational components, schemas, data standards, metadata standards, data hubs, open access funding models and so forth (see Chan *et al.,* (2001) for some definitions). The more interesting question is how an SDI may become more than the sum of these parts? Technological aspects seem to have received less attention recently, perhaps because the necessary organisational developments are lagging behind technical capacity. However as (Cantán1, Zarazaga-Soria et al. 2006) observe, many technical problems remain, and future developments such as greater interaction with mainstream Information

Technology (IT) and more advanced services (Cantán1, Zarazaga-Soria et al. 2006; Masser, Rajabifard et al. 2008) will place additional demands on the technology supporting SDI (Muro-Medrano, Poveda et al. 2005). Current research is focused more on the necessary legal and institutional frameworks for SDI e.g. (Erik de Man 2006) and the political, e.g. (Zarazaga-Soria, Ogueras-Iso et al. 2004) and social context e.g. (Harvey 2003). Research on these issues cuts across other differences of emphasis on the degree to which SDI are a means for identification of information via metadata e.g. (Hill 2006), for access to maps e.g. (Maguire and Longley 2005) or for inter-operability e.g. (Nogueras-Iso, Zarazaga-Soria et al. 2004; Nogueras-Iso, Zarazaga-Soria et al. 2005) although most authors seem to agree an SDI ultimately needs all of these elements. Harmonisation (i.e. agreeing classifications, scales and statistical bases) has so far largely been dealt with by calls for 'atomic units' to be agreed for 'core' (EC 2007) data sets (ISDI 2004; EC 2007) despite the fact that many data collection agencies have strong reservations about extending their support of map data beyond their own operational remits (Sang, Birnie et al. 2005). A more limited set of research instead proposes processes and methodologies for common spatial unit design in SDI e.g. (Eagleson, Escobar et al. 2001) and classification harmonisation e.g. (Zarazaga-Soria1, Nogueras-Iso1 et al. 2006) to maximise potential for reuse of the data. However, there are few examples of successfully implemented schemes, partly due to the institutional and sectoral nature of GI resources (Sang, Birnie et al. 2005). Thus there are moves for data harmonisation within various sectors e.g. geology (Asch, Brodaric et al. 2004), forestry (COST E45 2006), and soils (EC 2006) but few address the broader aim of defining spatial units to support socio-ecological research and management, perhaps because, as Moran et al. (2003) argue, this is a particularly complex problem (a few examples for wider approaches being Sang and Birnie (2008) and Zarazaga-Soriza *et al.* (2006)). Alternatively, this may only be an apparent weakness in SDI progress because relevant work in the GI community on the long standing issue of data integration (Openshaw 1984. ; Openshaw and Flowerdew 1987; Martin 1996) is not yet set in a specifically SDI context (as per. Duckham and Worboys (2005) although specific work within the SDI community is beginning (Mohamadi, Rajabifard et al. 2009). Beyond general calls for data to be 'fit for purpose' (EU 2007), very little research is looking at the harmonisation problem as not only between data sets but between data and end user processes, Masser *et al.*(2008) being among the first to explicitly raise this as a separate issue.

Williamson et al. (2003) attempt to provide a conceptual framework into which the various forms of SDI may fit at each stage of their development. Their primary distinction is between those focused on product creation (i.e. metadata databases and centralised data clearing houses) and those focused on the processes which facilitate existing data providers and users to communicate directly via services with user generated content. Through a series of books and papers (Williamson, Rajabifard et al. 2003; Williamson, Rajabifard et al. 2006; Rajabifard 2007) they argue that process-based SDI are more common at larger management scales and in more advanced stages, being more organisationally feasible and flexible. They see SDI development following a standard 'S' shaped diffusion curve in terms of adoption (Rajabifard, Feeney et al. 2002) with most countries still being at a very early stage, and only a few e.g. Australia, the USA and Canada adopting a process-based approach early on, aided by their federal political structure. Today Norway might be included as a relatively advanced example in a non-federal state (Strande 2006). The approach provides some useful insight, not so much into what an SDI *is* but what one is intended to *do*. (Figure 3).

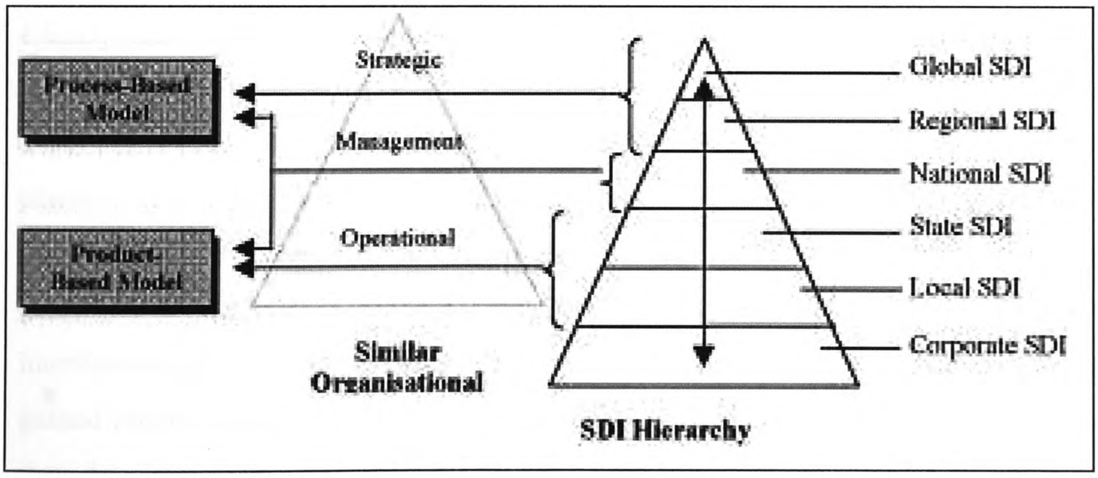

Figure 3 : The relationship between scale of SDI, function, and kind of SDI according to Rajabifard et al., 2002 (Figure 5 from Rajabifard et al., 2002 reproduced by kind permission)

Figure 3 shows Rajabifard et al.'s (2002) view as to how organisational hierarchy relates to SDI at various scales and thus to process or product based approaches. The argument is that at small scales, where management of complex systems is both possible and necessary to deal with the specifics of collating and delivering actual data, an SDI needs to adopt a product-based approach. Thus, local planning departments might implement a single database with a common local co-ordinate system to which all data sets are converted. In this case a single co-ordinating body (Sang, Birnie et al. 2005), is present which can over see issues of access rights, costs, data consistency and metadata provision. The system may not be flexible enough to respond to a broad range of end users but its chief purpose is to provide timely, accurate, spatially explicit data to support on the ground decision making for one organisation.

Higher up the pyramid, SDI are needed to support research and monitoring of the performance of the operational level (Rajabifard, Feeney et al. 2002). Thus, an SDI needs the ability to provide more abstract metrics of the decisions being undertaken at the operational level and the data used in support. So for example, regional planners may wish to see the cumulative effect, and alternative possibilities, of the decisions made by landscape planning offices in their area. At the highest, strategic level, agencies need output from the SDI of simple indicator metrics by which to measure policy effects.

Clearly such an SDI is not provided within the 'product' method. Simply collating data into a single database may not mean it is 'fit for purpose' (EU 2007; Masser, Rajabifard et al. 2008) in a complex planning application. Nor does it provide regional planners with analytical data on decisions made at the local planning office in the form of high level metrics. A limited view of the 'process' based SDI (where the definition is restricted to processes for standardising data identification, access and interoperability) does not cover this either. "Just because different information can be gained about a state for example from different jurisdictional levels, does not mean that the information will necessarily be compatible (it may not be of the same accuracy or have the same specifications, utilize the same symbology etc.)" (Masser, Rajabifard et al. 2008 p.14). Masser et al. (2008) go on to argue that, beyond the technical issues of data identification and access, "the key challenge is how to develop a spatial data infrastructure (SDI) that will provide an enabling platform in a transparent manner that will serve the majority of society who are not spatially aware" (Masser, Rajabifard et al. 2008 p.5). One aspect of 'fitness for purpose' therefore is any purpose by which data are visualised or analysed for presentation to the general public in a format (e.g. 3D visualisation) for which it probably was not intended. The processes that transform the data to particular end uses are themselves part of an SDI where by the original information and the processes applied (with their consequent uncertainties), need to be linked directly to higher level metrics and strategic plans. It is to this broad view of SDI which this discussion aims to contribute.

1.5.2 Portals and democratic engagement in SDI

'GI Portals' (Maguire and Longley 2005) are intended to ensure spatial data are collated centrally and are accessible. For example the EU Geoportal (JRC 2007; Kanellopoulos 2007), the NASA Earth Science Gateway USA (Alameh, Bambacus et al. 2006) and Virtual Australia (Masser, Rajabifard et al. 2008) are aimed at the general public while EDINA and MIMAS (Higgins, Medyckj-Scott et al. 2004) and GOS (Masser, Rajabifard et al. 2008) are mainly of use to professionals with the relevant knowledge and software to use their information. Arealis (Strande 2006) serves both types of user, providing on-demand map services to the general public and restricted access data download services to those with a particular interest. While issues as to their utility (Crompvoets, Bregt et al. 2004) and uptake (Maguire and Longley 2005) remain, efforts are being made to address these limitations. INSPIRE (EC 2007) has adopted the ISO 9115 and 19119 meta data standards (EC 2007), as have Australia and New Zealand (ANZLIC 2007) which should lead to a wider range of data being contributed to portals as more data is produced to the common standards, removing one cost barrier to participation. Although in the USA the Federal Geographic Data Committee continues with its own standard (FGDC 1998) the emergence of XML and GML as de facto global data query standards mean that the issue is more one of semantic consistency than interoperability (Nogueras-Iso, Zarazaga-Soria et al. 2004; Hill 2006). However semantic descriptions of qualitative features and automated production of meta-data is a challenge, particularly as regards searching for imagery by semantic spatial relationships (Bertolotto 2006; Khan 2007). It is an interesting example of the need to integrate spatially intelligent processes within the SDI service functions, even at the fundamental level of data identification, and here also current SDI initiatives remain too 'product' focused (Williamson, Rajabifard et al. 2003; Georgiadou, Puri et al. 2005). For example, institutional portals are developed rather than, say, providing a clearing house and competitive testing standards for automated semantic tagging to which other online portals can refer.

1.5.3 Harmonisation

Projects interested in harmonization of data are not well developed (Sang, Birnie et al. 2005). Although INSPIRE does aspire to achieve harmonization (EC 2007) this may yet prove easier to say than do as there is often an inherent tension between data collection strategies for different purposes (Sang, Birnie et al. 2005). While Huby et al. (2007) argue that the domain of the data is less important that its characteristics such as raster or vector, qualitative differences in the data of interest are particularly wide between socio-economic and bio-physical domains. A key difference is that anthropogenic data creates greater concern for confidentiality and so large minimum unit size (Sang and Birnie 2008). Yet data harmonization does hold the potential for huge cost savings in both data collection and improved decision making (Wang, Song et al. 2007) hence considerable interest in Joined Up Government generally (Al-Hakim 2007; Wang, Song et al. 2007) and the so called 'n-initiatives' in the UK in particular (Buchanan 2005; Sang, Birnie et al. 2005). It is also fundamental to ensuring data is 'fit for purpose' for many cross compliant policy analyses (Sang, Birnie et al. 2005). Nonetheless TIGER, the SDI of the USA Census Bureau (Carbaugh and Marx 1990), remains exceptional in the range of attributes collected by a common spatial base (Sang, Birnie et al. 2005). In the UK the Joined Up Geography Testbed run by Manchester Geomatics (see Sang et al. (2005)) has provided greater operational understanding of data integration issues for those involved, but results are (unfortunately) confidential. The Digital National Framework geo-referencing system (Rackham 2006) may lead to an emergent set of commonly used referencing units, but the statistical implications of its use are unclear because Ordnance Survey will not maintain an update history, leaving this to licence holders (Sang, Birnie et al. 2005).

Most harmonization work is either still at the research stage or early implementation stage (COST E45 2006; Huby, Owen et al. 2007), perhaps because the MAUP issues appear so complex, or because this only becomes a problem once the pressing issues of data identification and access have been solved, making data interoperability "last in terms of priority for future SDI development" (Masser 2005 p.14). Yet, as Lausch and Herzog (2002) point out, data harmonization at relevant scales is essential for the development of landscape monitoring indicators to be robust. They go on to state that harmonization of data processing is also required including the formats and scales into which data is transformed prior to its analysis (Lausch and Herzog 2002).

1.5.4 Automatic visualisation through portals – the next step in SDI

One area that draws these issues together is the visualisation of information. Firstly visualisation takes data from multiple sources with their respective mapping methods and scales, and models their combined output at a range of scales. Scales range from near to real world in the foreground of Virtual Landscape Theatres (e.g. www.hutton.ac.uk/learning/exhibits/vlt), to very small scales in the background. Secondly, the terrain models themselves distort the data from flat maps back to surfaces in three dimensions, changing any values related to area, density or shape (Germino, Reiners et al. 2001; Sang, Ode et al. 2005; Sang, Ode et al. 2008). Thirdly, the images produced from such processes can be deceptively impressive in terms of level of detail, perhaps giving undue apparent validity (Appleton, Lovett et al. 2002; Appleton and Lovett 2005), yet are most often used because they can convey a message to those in the community with least training in spatial information interpretation (Appleton, Lovett et al. 2002) and hence are believed to improve democratic involvement in planning processes. Automated solutions to the issues raised by the visualisation of data will come to the fore if, as Bishop and Lange predict "the next step is a movement towards automated development and display or distribution of three-dimensional models from online SDI" (Bishop and Lange 2005 p. 261).

1.5.5 INSPIRE – an SDI for landscape management

For landscape planning, the currently most significant SDI development is the Infrastructure for Spatial Information in the European Community (INSPIRE) (EU 2007). The stated aim of INSPIRE is:

> "The infrastructures for spatial information in the Member States should be designed to ensure that spatial data are stored, made available and maintained at the most appropriate level; that it is possible to combine spatial data from different sources across the Community in a consistent way and share them between several users and applications; that it is possible for spatial data collected at one level of public authority to be shared between other public authorities; that spatial data are made available under conditions which do not unduly restrict their extensive use; that it is easy to discover available spatial data, to evaluate their suitability for the purpose and to know the conditions applicable to their use."

(EU 2007 paragraph 6)

INSPIRE is the culmination of a number of initiatives (Longhorn 2007) precipitated by recognition that Europe was lagging behind the USA in developing the spatial information industry. The particular themes on which INSPIRE has come to focus, primarily environmental (EU 2007 paragraph 1), reflect the fact that environmental issues are cross-border and therefore require data from multiple countries to achieve an appropriate overview. This is in the context of requirements of other European legislation for land management at a landscape scale e.g. the Water Framework Directive (EU 2000), the European Landscape Convention (Council of Europe 2000), the Soils Directive (Dusart, Lagacherie et al. 2006; EC 2006) and in particular the operationalisation of this legislation within Environmental Impact Assessments (EIA) and Strategic Environmental Assessments (SEA) (Vanderhaegen and Muro 2005).

The focus on landscape units raises the question of what precisely is the 'landscape scale', particularly when there are multiple scales of landscape (Partidário 2007). One route is to simply look at divisions and transportation links for biophysical properties such as nutrients, or energy food webs. Many of these are constrained by water catchment areas (Kie, Ager et al. 2005) which coincide with viewsheds in some landscapes (Miller 2001). However, EU legislation has embedded within it the principle of subsidiarity and with that, local democratic control of decision making (Jones 2007) implying information must be provided at a scale to which people can relate. Anthropogenic definitions of landscape management units are much harder to define (Karstens, Bots et al. 2007). Relevant scales are dependent on both ecological functions and the area for which people develop a sense of place, perceive the issues it faces and organize a response (Jaquez and Negra 2005) all of which have a visual element. Certain groups of people, (and indeed animals) may consider peaks and ridges not as the dividing lines of landscape units, but their 'skeletons' (Kent and Elliot 2000; Gold and Dakowicz 2005), the central locations by which a particular landscape may be seen and the features by which it is navigated (Bingman and Able 2002; Birkett 2003; Kie, Ager et al. 2005; Farina 2006; Holland 2006). Other interest groups would take a very different point of view, for example those living in cities may regard the areas visible from their homes, and so affecting property values, as higher priority (Luttik 2000), which would place boundaries along the occluding edges from given locations (which may not in fact be significant inflections in slope).

Planners therefore face an issue of how to measure the impact of developments for groups whose interests fall within with multiple spatial units, some of which are perspective specific. They must also consider how to balance the majority opinion against spatial minorities (Sang and Birnie 2008) whose particular experience of developments will pertain not only to the their physical location(s), but the combination of landform and land cover they can see (Sang, Ode et al. 2008). To meet INSPIRE's aspiration of providing information 'suitable for the purpose' of democratic local involvement in land use planning therefore, goes beyond the provision of limited portals for map viewing, or even data download, to the on-demand visualization of data called for by Bishop and Lange (2005).

1.5.6 Environmental Impact Assessment and INSPIRE

One of the key drivers behind INSPIRE has been the requirement of the Environmental Impact Assessment Directive (EEC 1985; EC 1997) that member states take an integrated overview of the environmental implications of any proposed development[3]. In the majority of cases this means assessing the effect of infrastructure

[3]In the US the National Environmental Policy Act (NEPA) also set up similar EIA (Marsh, 1983).

development such as energy installations and waste disposal (Vanderhaegen and Muro 2005), for which visual impact is a significant factor (Wilson 2002). Vanderhaegen and Muro (2005) review the potential contribution of SDI to the EIA process, including a survey of practitioner's views. They conclude that between 1900 and 3500 million Euros per year are spent on EIAs and SEAs (Strategic Environmental Assessments), of which around 100 to 230 million Euros could be saved by the introduction of an SDI to support the process. These figures should be regarded with caution given the size of the survey and the assumptions on which they are based, however the authors also conclude from a qualitative analysis of responses that the current limitations on data acquisition and compatibility have a material impact on the quality of the decisions made, in particular the "probability of ignoring important environmental issues or over-looking potential impacts" (Vanderhaegen and Muro 2005 p.138). Respondents expressed concern that some impacts could not be reliably quantified and that this may determine whether or not a particular proposal was given planning permission. Whilst the particular kinds of impact of concern are not specified, visual impacts are both a significant part of the EIA's in Europe and the USA (Wilson 2002; Marsh 2005) and very difficult to quantify (Tveit, Ode et al. 2006). Practitioners also stated that presenting information in an understandable way to the public was difficult as a consequence of problems with spatial data availability and quality. Whilst 91% of respondents used GIS to visualise data (Vanderhaegen and Muro 2005), it is known from other studies that simulation and 3D scenario representation is not commonly used within planning processes (Appleton, Lovett et al. 2002; Paar 2006). This is partly due to concerns as to the legitimacy of the visual results (Appleton and Lovett 2005; Williams, Ford et al. 2007) despite research arguing the method is comparable to photographs (Bergen, Ulbricht et al. 1994) but also the lack of analytical methods with which a planning process can interpret the resulting feedback when individuals have travelled different routes around a 3D model (Bishop, Ye et al. 2001; Appleton and Lovett 2005). This is particularly problematic at higher levels of management where statistical abstraction is required to achieve an overview (e.g. SEA might equate to Williamson et al.'s (2003) 'monitoring' level).

Any attempt to improve the utility of spatial data for informing public consultation must therefore address both issues of the validity of data-visualisation and the validity of analytical metrics in 2D and perspective. However, while the provision of services (i.e. software or online services) may include some measure of the fitness for purpose of data for visualisation or production of visual metrics, actually improving those measures would require a concomitant change in data collection and production methods. Visual analysis, therefore, must be recognised within the wider SDI initiatives, as one of those 'purposes' for which the data needs to be 'fit' at the point of collection.

1.6 SDI in landscape planning and research

Marsh (2005 p.3) defines landscape planning as "the macro environment of land use planning activity dealing with landscape features, processes and systems." Marsh identifies three general 'realms' of landscape planning, the information support for which matches with Rajabifard and colleagues' general model of SDI (Figure 4).

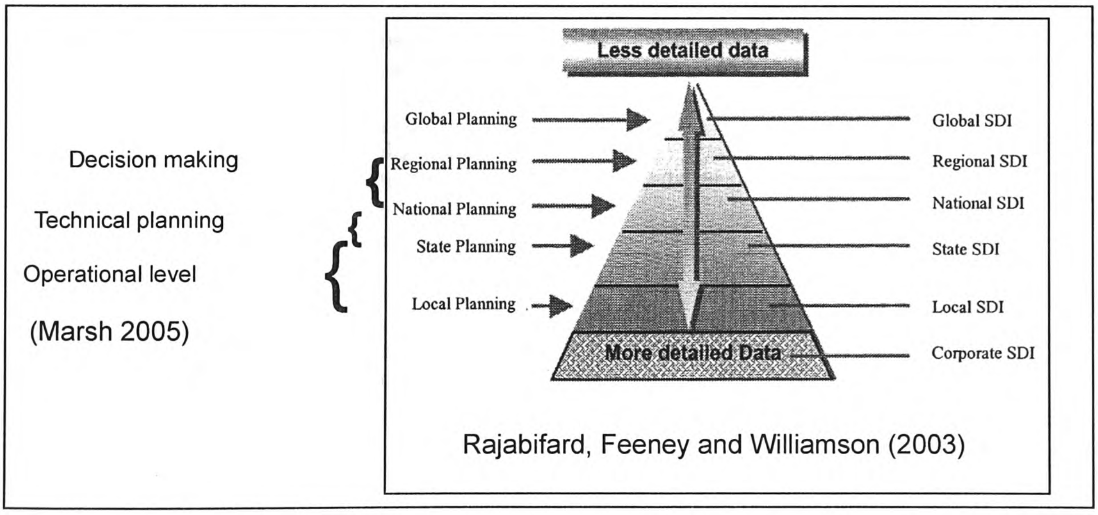

Figure 4 : Landscape Planning related to the Rajabifard and colleagues' general model of SDI (Inner-box Figure 2.6 from Williamson, Feeney and Rajabifard 2003 reproduced by kind permission).

These are discussed in more detail as follows:

1. At the 'operational level' (Rajabifard, Feeney et al. 2002) the task of SDI would be to support 'landscape design', i.e. "the laying out..[of].. the

configuration of uses, features and facilities that are to be built, changed or preserved" (Marsh 2005 pp. 13-14). Information requirements at this level would be for accessible, consistently referenced and thematically compatible maps which are appropriate for use in preparing visualisations and for presentation to the public.

2. At the 'Management level' (Rajabifard, Feeney et al. 2002) SDI can support "Technical planning" in landscape management, i.e. the "various processes and services that are used in support of both decision making and design activities" (Marsh 2005 p.13). This is closer to EIA measures, such as predicting effects on ecology or quality of life, and information resources would be needed both for detailed maps and to produce more abstract metrics to allow objective comparisons between alternative plans as well as for reporting to the decision making level (e.g. for national monitoring schemes (Dramstad, Fry et al. 2001).
3. 'Strategic SDI' (Rajabifard, Feeney et al. 2002) are needed for "Decision making" (Marsh 2005 p.13) i.e. "that activity related to the decision making process itself, which is usually carried out in conjunction with or directly by formal bodies such as planning commissions... It involves building the methods and means for arriving at planning decisions ... [including] consolidation of technical studies, formulation of policies, articulation of goals, definition of alternative courses of action and selection of preferred plans." (Marsh 2005 p.13). The decision making level thus relies primarily on summary information, consolidated into reports and abstracted to general policy goals. Access to lower level information would also be required for some functions however, such as selection of preferred plans.

The planning field thus exhibits many of the properties of a hierarchy highlighted by Williamson *et al.* (2003) :

> Part-Whole Property: An element on a higher level consists of one or more elements on a lower level.
>
> Janus Effect: An element of a hierarchy has two different faces, one looking towards wholes in a higher level, the other, towards parts in the lower level.
>
> Near Decomposability: Those elements near each other in the hierarchy interact more strongly.

It is unlikely that the decision making level will communicate directly with the design level without going through technical planning. Arguably however, one role of SDI might be to challenge this by allowing swift transformations between information at each level, allowing decision makers to trace where abstracted information has come from, and designers to trace the cumulative effect of previous plans/developments from different sources.

Landscape planning is also distinguished from environmental planning, the latter being a "'catch all' sort of title applied to planning and management activities in which environmental rather than social, cultural or political factors, for example, are central considerations" (Marsh 2005 p.3). The implication is that these excluded factors are included within the landscape planning definition. Yet Marsh's primary distinction between landscape planning and other disciplines is spatial, being planning undertaken at the 'site' or 'regional' scale:

> Site: "local parcels whose size usually ranges from less than an acre to hundreds of acres, with a simple ownership or stewardship arrangement."
>
> Region: "geographic settings that house communities, either a single community and its rural hinterland, several communities and the systems connecting them, or a metropolitan area with its inner city, industrial and suburban sectors."
>
> (Marsh 2005 p.4)

Although the first definition does give an approximate absolute size range, the two definitions are essentially identifying a spatial scale at which social, cultural and political aspects of human society converge to form distinct spatial units. The spatial boundaries of such units may be vague and variable in extent but it is an important rationale that landscape planning be carried out within anthropogenically relevant units.

1.6.1 Landscape scale: Cultural or innate?

Some would argue that the rationale for what constitutes an anthropogenically relevant landscape unit runs deeper than societal constructs, being naturally rooted in the human psyche (Kaplan and Kaplan 1982 pp.73-114; Appleton 1996; Lothian 1999; Bell 2001; Farina 2006). This view connects with the Romantic philosophy of landscape whereby nature should be "given consideration for its own sake and for its beauty [and] spiritual meaning" (Marsh 2005 p.8). In order to remain objective this must be without yielding to what John Ruskin termed the 'pathetic fallacy' (Landow 1971) whereby internal response distorts physical 'truth', so rendering the prospect of evidence based design theory (Bell 1998 pp.5-9) almost impossible as all experience is subjective (as per Jaques (1980)). In modern parlance, there is some identifiable 'ecosystem service' which the environment provides for quality of life (Brandt and Vejre 2004) the changing components of which can therefore be used to separate areas according to peoples innate response to the kind of landscape they constitute.

Since, for the majority of people, the largest part of their experience is visual (Bruce, Green et al. 1996), it is not surprising that aesthetics constitute one of the three pillars of EIA in the U.S. (Marsh 2005 p.16). They are also an 'essential component' of European EIA (Wilson 2002), and indeed Scottish National Heritage (SNH) devote about two thirds of their advice on the environmental impacts of wind farm and hydro-electric development to visual factors (SNH 2001). However, to understand why Vanderheagen and Muro's respondents (Vanderhaegen and Muro 2005) might find aesthetic quality difficult to include in the balance of factors relative to an EIA decision, one need only try relating them to the stages of preparation of an EIA plan (as per Marsh (2005 p.15)):

- Select variables or factors that are pertinent to the problem and make an inventory.
- Formulate alternative courses of action.
- Forecast the effects (or impacts) of the alternatives.
- Define what will be gained or lost by choosing one alternative plan over another.
- Evaluate and rank the alternatives as to preferred outcomes.

Each of these stages raises difficult questions as regards aesthetic impact. Which measurable variables are pertinent to landscape character? What will be the visual effects of different plans, and seen from where? Something might be measured as changed, but is this positive or negative? Can one rank alternatives as to aesthetic beauty in a way that most stakeholders will agree with? It is to answer these kinds of questions that research is conducted into landscape design and management e.g. (Rodiek 2006; Tveit, Ode et al. 2006).

1.6.2 SDI in landscape research

Landscape research is a very broad field, including studies of designs (Manning 1995; Rodiek 2006) which would act as a repository of knowledge and opinion on which operational level processes might draw (Selman 1998), policy analysis (Rodiek 2006; Brunetta and Voghera 2008) and work of direct relevance only to the decision maker (Emmelin 1996).

Ode (2003 p.13) breaks down the field by a hierarchy of intra-discipline paradigms, however, the focus in this thesis will be only on that aspect which seeks to link the 'Objectivist' and 'Subjectivist' paradigms (Lothian 1999), specifically research into what it is about landscape which creates the perception of 'beauty and spiritual meaning'. There are many subsections within this category, particularly between those attempting to identify quantitative measures of landscape e.g. (Jessel 2006; Ode, Tveit et al. 2008) and those focusing on qualitative methodology e.g. (Moor-Colyer and Scott 2005). Given the pressure from legislation such as the European Landscape Convention and the EIA process for objective comparison of competitor plans (Vanderhaegen and Muro 2005; Jones 2007; Thórhallsdóttir 2007), and objective monitoring of cumulative impact[4], including visual impacts (SNH 2004), it is on the former that attention will be focused here (Gaber (1993) argues for the qualitative research case).

Of the various methods by which landscape preference may be quantified a common element is the use of perspective views of the landscape as the primary means to elicit people's preferences. This is true regardless of whether the medium is traditional physical photographs e.g. (Shafer and Brush 1977; Kaplan and Kaplan 1982; Moor-

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[4] The professional website and forum 'EIAVault.com' provides a collection of literature on cumulative impact ; www.eiavalt.com/categories/CEA_References

Colyer and Scott 2005; Dramstad, Sundli-Tveit et al. 2006), 2D computer visualisations (Burrough and McDonnell 1998; Daniel 2001; Ode, Fry et al. 2009), or fully navigable 3D environments (Bishop, Ye et al. 2001; Daniel 2001; Miller, Morrice et al. 2005). It is also true regardless of whether the image is photo-realistic e.g. (Gómez-Limón and Vicente de Lucío Fernándezb 1999), an artistic impression e.g. (Willis and Garrod 1999; Bateman, Jones et al. 2006), realistic but clearly computer generated (Ode, Fry et al. 2009), or in abstract form e.g. by silhouette (Hägerhäll, Purcell et al. 2004). These visual prompts have been used in combination with various survey methods, including in-depth interviews (Ohta 2001 ; Moor-Colyer and Scott 2005), postal surveys (Moor-Colyer and Scott 2005), online surveys (Ode, Fry et al. 2009), and (to remove verbal ambiguity from the response data) technology such as attention monitoring (De Lucio, Mohamadian et al. 1996). Methodology, in particular the scope afforded within a question for broadening one's response beyond preferences between specific images, can affect the significance of the particular viewing location presented (Scott and Canter 1997). However, even where a strong trend is elicited from multiple studies (e.g. the case of forest juxtaposed with water (Kaplan and Kaplan 1989; Kaltenborn and Bjerke 2002)) view point dependency poses a problem in transforming this to an operationally usable measure within a planning process (Tveit, Ode et al. 2006).

To take the simple example of forest juxtaposed with water, how do planners rate the impact of development in a particular area when this juxtaposition is only apparent from some viewing positions? Cartographically, the two types of land cover may not be adjacent, or they may be adjacent but this is not visible from key locations, or indeed may not be visible but still relevant due to human interpretation of correlated landscape elements (Kaplan and Kaplan 1989; Dramstad, Sundli-Tveit et al. 2006; Sang, Ode et al. 2008). In addition, the issue is self-evidently more complex than that of simple adjacency of two land cover types. A commercial spruce forest adjacent to a square reservoir does not generally evoke the same sense of natural beauty as natural lakes and woodland. More refined indicators of naturalness are needed such as shape complexity and patch size (McGarigal, K. et al. 2002; Ode, Fry et al. 2009). However these indicators may also be highly sensitive to the view point chosen and how the perspective view has affected the available data for that view point (Germino, Reiners et al. 2001; Sang, Ode et al. 2008). So, a particular problem is how to choose a view point which: (i) provides a representative view of the landscape as a whole, as might be qualitatively selected by a researcher or planner; (ii) is representative of the overall model of that landscape (i.e. land cover data and DEM combined). Only if these issues can be successfully dealt with can metrics be measured for the view on which preference is expressed and then extrapolated to elsewhere.

In all these perspective-based approaches, the responses being measured may be to features which are not consistently represented by the perspective and map data (Sang, Ode et al. 2008). The cartographic paradigm of the planning process as regards identification of 'objective' measures at the technical level and indicators of cumulative policy impact at the decision level is a barrier for translating preference research conclusions into practice (Paar 2006). If one assumes that cartographic representation will continue to be the primary format of communication and decision making in landscape planning, the task for SDI is to: (i) provide systems by which research conclusions based on perspective studies can be applied to operational maps at the design level, and (ii) perspective relevant metrics of landscape quality and change can be coded into maps for the technical and decision making levels. As technology allows increasing use of 3D modelling, virtual reality and computer visualisations of scenarios of landscape change, such a system must also be able to take account of the fitness of input data to such uses and communicate this in an intuitive manner.

1.7 Conclusions: Requirements of an SDI to support EIA and landscape research

From the above discussion, seven key functions have been identified as necessary for an SDI to support the visual component of Environmental Impact Assessment.

a) SDI need to ensure support for the *processes* to which data will be subjected at the operational level within landscape planning, foremost of which are integration, visualisation and dynamic updating.
b) Metrics need to be available by individual viewpoint if they are to be parameterised using outputs from preference studies. This entails the potential to test relationships between preference and the spatial patterns in both the 2D view plane and its viewshed on the map. However, they must also provide the option for widening the spatial information to hidden areas of the scene if

contextual factors and theories of human environmental cognition are to be investigated.

c) SDI need to support the generation of summary metrics of landscape change to supply the technical and decision making levels required in landscape planning.
d) To minimise issues of sample bias, metrics are needed which relate to the individual and can be dynamically calculable along individual paths through 3D environments. They must also however be suitable for generalisation and mapping, in order to provide operationally useful information for planners.
e) Where logistical barriers exist to the use of navigable models, metrics are needed to indicate the degree to which a set of example viewpoints is representative of the possible range of views onto and within an area.
f) Metrics need to take into account information on the robustness of data for representing the view from a particular view point, including issues of visualised versus map scale, and data heterogeneity within partially visible spatial units.
g) An SDI (as a system) should be able to take potential utility for visualisation into account in the designation of collection units. Thus, some means to optimise between visually robust units and other statistical and operational demands should be possible.

Point (e) above argues that there may be cases where, for logistical reasons (i.e. outwith the bounds of a technical solution), it might be necessary to provide a limited number of fixed images of proposed landscape change. For example there may be cases where too few people could access the information within a virtual environment (e.g. Virtual Landscape Theatre) or groups without easy access to the internet. The problem of viewpoint selection remains therefore a fundamental issue in landscape research, management and planning. Section 2 will propose the use of 'Euler Zones' (areas within which the graph complexity formed by horizons in a view does not change), as the minimum representative set of viewpoints. This Euler number might also prove a relevant metric in itself since research suggests that topology is cognitively significant (Mark and Egenhofer 1995; Mark and Turk 2003). Indeed the eminent 20th Century environmental psychologist James Gibson effectively sets out the principle of a visual set topology in his depiction of visual 'solid angles' (Gibson 1986)[5], and Jay Appleton highlights the importance of contrast across horizons and

[5]This is true even if Gibson did not accept the idea of the "retinal image" (Marr, 1982), arguing instead that the mind measured invariance across and between the signals received at the retina, since

occluding lines for his prospect-refuge' theory (Appleton 1996 p.127 and p.182) (see also Connolly and Lake (2006 p.233) for an application of this in archaeology). The role of topology as a metric is considered in Section 3, however, in terms of developing an SDI, the Euler number provides a (pragmatically) finite number of locally stable, view point relevant units within which other metrics e.g. (McGarigal, K. et al. 2002) may be measured, attributed variance statistics, and hence aggregated for use at higher levels in the SDI hierarchy, fulfilling the requirement of point (c) above. By the same reasoning, the boundaries to the Euler zones would be priority lines to include in any optimisation of the collection units for mapping land cover where account is taken of potential future uses of the data set in visualisation.

Not all aspects of view 'quality' can be directly represented by a binary map of visibility. The morphology and arrangement of specific views is clearly important, and ideas regarding one's ability to draw on contextual information (e.g. to remember or predict a feature as being just out of sight) are well supported by psychology literature (Kaplan and Kaplan 1982; Appleton 1996). It is important therefore, that any method to map visibility maintains links between a location's position in the view and its geographic location so that the data behind an occluding boundary can be queried (point (b)). These links are also important in order to meet criterion (a) in that GIS tools are likely to be used for data integration and update and so generally use orthographic projections, whilst visualisations are perspective based. Given the scale and geometric transformations between map and visualisation, any attempt at unsupervised generation of visualisations, say via a planning portal, must be accompanied by appropriate information as to the robustness of the data to that end (point (f)), with for example, consideration of the differences in area, or RMSE in shape. Again, this involves linking scene and data directly to allow automated analysis of the visual output for comparison with the original data. Any such visualisations will need to ensure that the view provided is representative, either via some cognitively relevant definition of a limited number of representative viewpoints,

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occluding edges would be sources of high invariance both spatially and with movement of the view point.

or a dynamic navigation of the scene and analysis of the view path history at the time of each response (point (d)).

Perhaps the greatest challenge from an SDI perspective will be to raise the profile of visual factors as a significant issue at the point of data collection (point g). EIA are one of the primary uses of land cover data, and visualising landscape change is a key factor in regulating societal response to environmental change (Bishop and Lange 2005 pp.3-4). However, collecting land cover data in a manner relevant to visual analysis is not currently considered. This adds an additional layer of complexity to Moran et al.'s (2003) 'great challenge', namely to design units of collection and analysis which reflect the ephemeral, transitory and perspective nature of human experience.

2 Section 2 - Visual Topology: Extending the Euler Characteristic to support analysis of visual relationships

2.1 Introduction

Section I set out why a topological landscape metric would be useful for generating visual basic spatial units, primarily in order to support summary metrics of landscape character that can be based on and mapped to representative viewpoints. This section advocates one potential measure as a candidate for such a metric. In doing so it introduces an area of topology which has not received much attention in the field of GIS, that not of the actual relationships between objects and regions, but of those relationships which occur in the two dimensional space produced by a perspective view in three dimensions. The idea stems from problems faced in the field of landscape research, and therefore begins with some examples from this topic to illustrate the issues before giving a brief history of topology in general and graph topology in particular. Space permits only an overview to demonstrate the number of branches to the subject and the generic power of the concept of 'ordering' as distinct from measuring. Visual topology quite literally adds a dimension, thus there are potentially many branches to be explored which could lead to an unwieldy story, so the focus will be on setting out the core theoretical ideas as developed with respect to the context of landscape analysis.

Ode et al. (2010) discuss the role of visual topology as a factor in landscape complexity and sets out a general approach to investigating its function in landscape perception. Section 5 demonstrates the concept's utility in landscape research and provides initial indications as to the shape of its response function with preference, while Sections 3 and 4 discuss its computation.

2.2 Topology in landscape perception

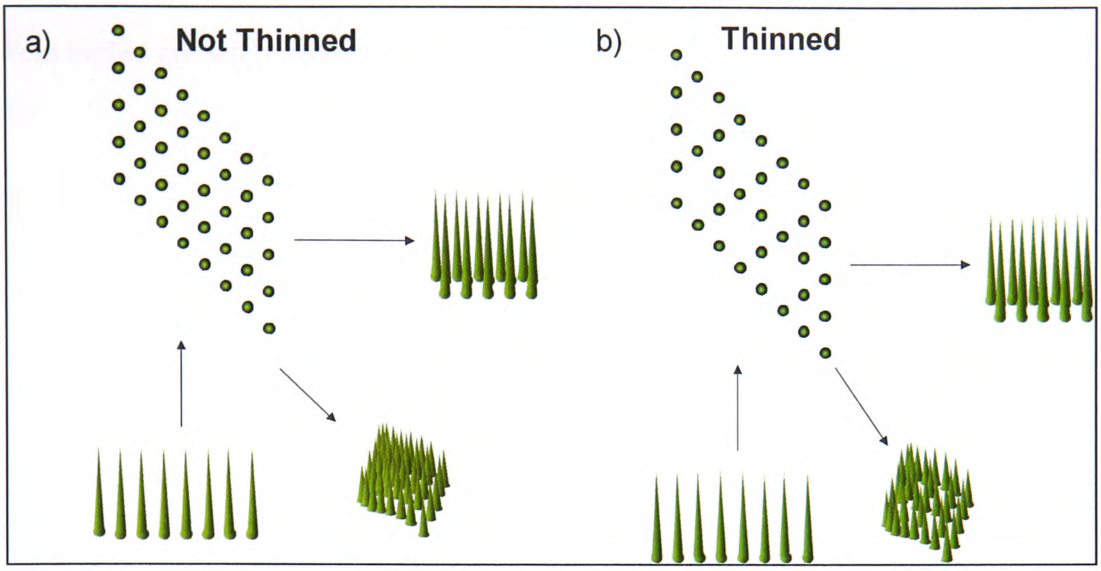

Figure 5 : Effect of Forest Thinning as Seen from Different Angles

The simplest issues of topology in landscape are those which can be modelled as point distributions. For example, in forest management strategies it is often argued that geometric arrangements of trees should be avoided as this looks un-natural (Lucas 1991). However, thinning forests in a manner which is both efficient and achieves the goal of apparently natural formation of the trees which remain is a challenge to forest managers. In particular, patterns can be apparent from some viewing angles but not others (Figure 5).

Some wind farm developments address the same issue with the opposite goal, to align turbines so that they present the minimum visual footprint from certain angles or conform to existing lines in the landscape (University of Newcastle 2002; SNH 2004; SNH 2009). Although pattern is partly about regularities in distance, which will always change slightly with any small change in viewing location, the point at which individual trees or turbines appear to converge to form lines and walls, to exactly over-lap each other, or to produce larger geometric shapes are discrete events. They are the points at which apparent topology changes. For example a greater mixture of tree species, including less productive deciduous varieties, are sometimes placed around the edges of forests to provide a more aesthetic vista (Lucas 1991), and protect against wind damage. They may be left un-harvested to act as a screen for commercial forestry work. However, such a screen will be more effective from some angles than others and could produce a visually distinctive ring, or band, feature when viewed from higher ground (Figure 6a).

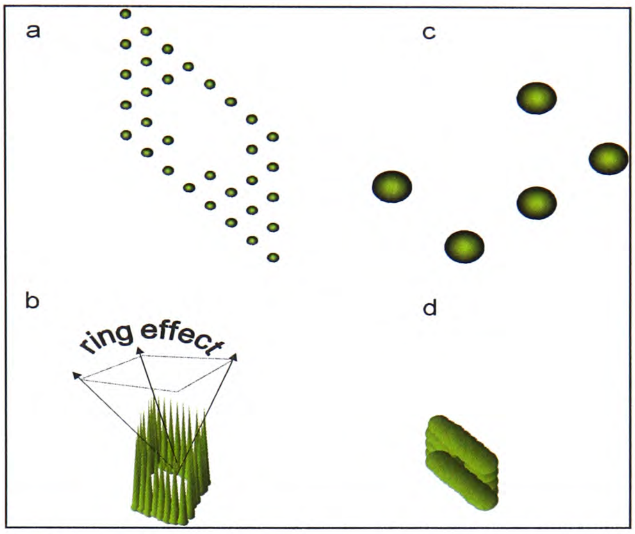

Figure 6 : Scale, Viewing Regions and Apparent Geometry – A 'ring' effect (a) from above (b) close up (c) in perspective (d) at distance

There are thus sites from which the visual quality of the same woodland is distinctively different when viewed from other sites. Although the apparent geometry of the woodland will change continuously between viewpoints, the ring characteristic would be invariant until such a viewing point is reached from which it ceases to be visible (Figure 6b). This is a property of the topology of the view, and its interaction with the geometry of the forest itself. Furthermore, the concept of the ring only exists at such a distance as the trees become a single visual object (Lucas 1991; Ogburn 2006). Close-up, there is no boundary between the cleared and un-cleared area (Figure 5c) yet further away, the trees converge to form a solid area, until, at greater distances, the clearing may not be distinguishable (Figure 6d), so the topological properties of the view are dependent on both viewing angle and scale.

Point distributions illustrate the key point, that of a discrete descriptor of spatial arrangement, remaining constant regardless of degree or scale. It also illustrates that for apparent or visual topology, this is also a matter of definition relative to the observer – of when the observer, human or machine, can no longer distinguish difference.

2.3 Topology: A brief background

Topology is the study of relative position (see Worboys (1995)). The utility of this concept was first demonstrated by Leonard Euler in 1735, who proved there was no solution to the 'Seven Bridges of Koningsberg' problem (Euler 1735) (see Leitzmann (1969)), and in the process demonstrated that it was ordering, rather than measurement which determined the problem. In particular, Euler discovered a formula (equation 1) relating the number of edges (e) and nodes (v) in a network to the number of loops that must exist (Figure 7a). The solution starts at 1 (no loops) and falls by one for each loop thereafter (for a readable introduction to topology in graphs/networks see Kinsey (1991)).

Equation 1 $$v - e = 1 \ldots 0 \ldots -1$$

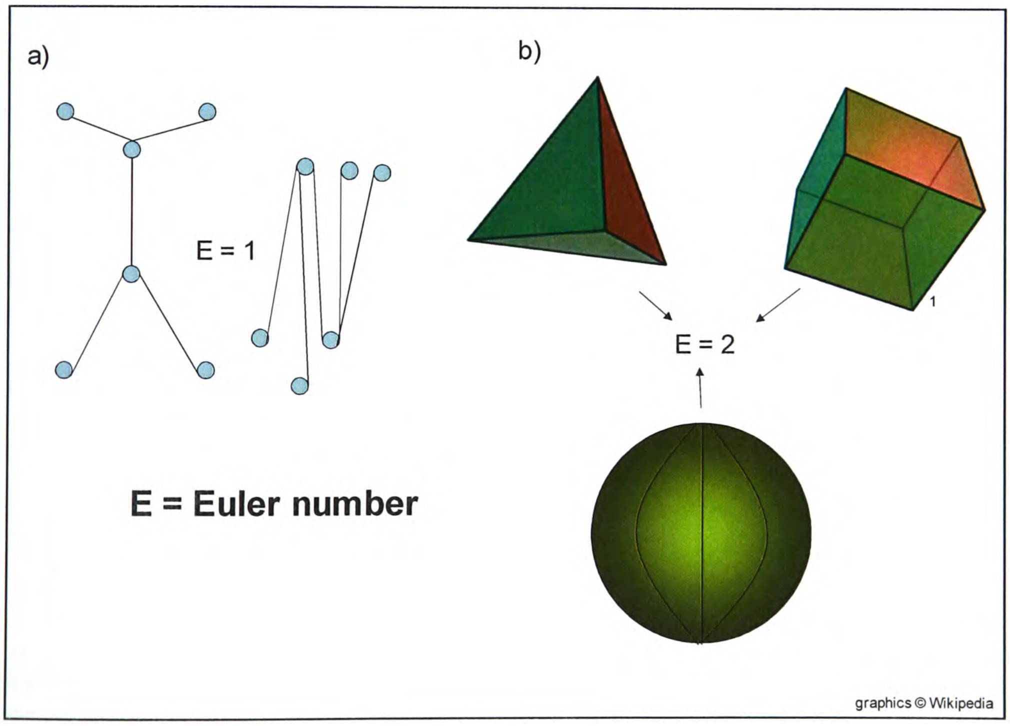

Figure 7: Homeomorphism: (a) Networks and (b) Shapes

In 1750 Euler went on to apply the same principle to polyhedra (Stander 1986). Rather than looking for relationships between the points, lengths and areas, Euler simply looked at the number of each type of element, to develop the formulae:

Equation 2 $\mathrm{E} = v - e + f = 2$

Equation 3 $\mathrm{E} = v - e + f = 2 - 2g$

Where: E = Euler number/Euler Characteristic (see Kinsey (1991) and Griffiths (1976)), v = number of vertices, e = number of edges, f = number of faces; extended by Lhuillier (Lhullier 1861) to include the effect of holes, as per equation *3,* where: g = genus of the manifold surface on which the graph is drawn (its 'number of holes')[6]. These two pieces of work by Euler split the concept of geometry into two separate components, relative position and absolute distance. By identifying position as a distinct property it could then be shown that otherwise apparently different shapes had important characteristics in common. Topological equivalence, or *homeomorphism*, means that one shape can be stretched to exactly match the other without changing the relative position of its vertices – that is the distances between vertices might change, but if vertex b is between vertices a and c, it will remain so, and edges will not therefore form new intersections. For example, a pyramid or cube could be 'inflated' to a sphere without relative translocation of vertices, so these shapes also have the same Euler number as one another[7] (see Figure 7b).

Pyramid	$4 - 6 + 4 = 2$
Cube	$8 - 12 + 6 = 2$
Sphere	$3 - 6 + 2 = 2$

[6]The formula is often referred to as Euler-Poincare formula as it was completed by Poincare Stander, D. (1986). "*The Euler Formula – Its History, Applications and Teaching, Teaching Mathematics and its Applications*, 5, 3, pp. 112-126.".with $\mathrm{E} = v - e + f - (l - f) - 2(s - g)$,where s = the number of separate shells (volumes). As we are working only on 2D and 2.5D manifolds – i.e. without volume, we only use the simpler version. It is also sometimes argued that Descartes had previously shown the formula $v-e+f=2$ for convex polyhedra.

[7]This need not hold in reverse.

The concepts are used today in many different applications such as network design in transport and utilities to ensure there is no over-dependence on any one node, (see Dekker and Colbert (2004)), cartography (to ensure say a house stays on the correct side of a river even if its position needs to be changed for reasons of representation e.g. Kulik, *et al.*, (2005), simulating kinetic actions in dynamic models (Dakowicz and Gold 2006) and modelling vague, semi-spatial concepts such as the social network (Dekker 2007). For this thesis its utility stems primarily from the fact that it describes a distinct aspect of shape which is of cognitive significance (Mark and Turk 2003) and which, unlike geometry, does not vary continuously with changing perspective.

The Euler measures of topology in networks and surfaces thus provide tractable, minimum, descriptors of the shape complexity of an object. As will be seen however, in order to establish general measures of apparent pattern in objects, the definition of topology must first be extended from 'which elements of an object are next to each other' in order to consider 'which elements of an object appear to be next to each other'.

2.4 Perspective and Visual Topology

Most work in the field of topology has so far assumed full knowledge of the objects (or regions) of interest and the space around or between them. In many circumstances however, an understanding of the topological characteristics of the object is built up from a partial knowledge, based on a particular perspective view. A similar problem is faced in the field of automated object recognition for computer vision, for which Plantinga and Dyer (1990) provide a brief history of relevant work. They develop three key concepts in particular: 1) the 'aspect-graph' - a graph linking each point on a sphere surrounding an object from which the view is topologically distinct; 2) 'aspect representation'- a simultaneous representation of an object from all points in the 'aspect graph'; 3) 'Viewpoint Space Partitions' (VSP) - each node on the 'aspect-graph' therefore, is the dual of a 'viewing region' - the area on that sphere which is delineated by VSP either side of which the apparent topology of an object changes.

Similar concepts are developed in this thesis, but from a different derivation, that of Euler's equation, as the interest here is in the net-complexity of an object rather than the detail of individual edge-node connections. This reflects a particular interest in measuring the visual complexity of landscapes, and the technical demands of large landscape datasets. However, it is worth recognising the parallels since there is much experience in the computer vision field from which GIS and landscape research could benefit. In this section the concept of topology is extended to take into account the effect this partial knowledge has on the apparent topology of the objects, i.e. the topology of that which can be seen. Here after, the 'Euler Character' referred to will be that of the graph produced by projecting the non-occluded boundaries of an object against a 2D screen, not the Euler character of objects themselves.

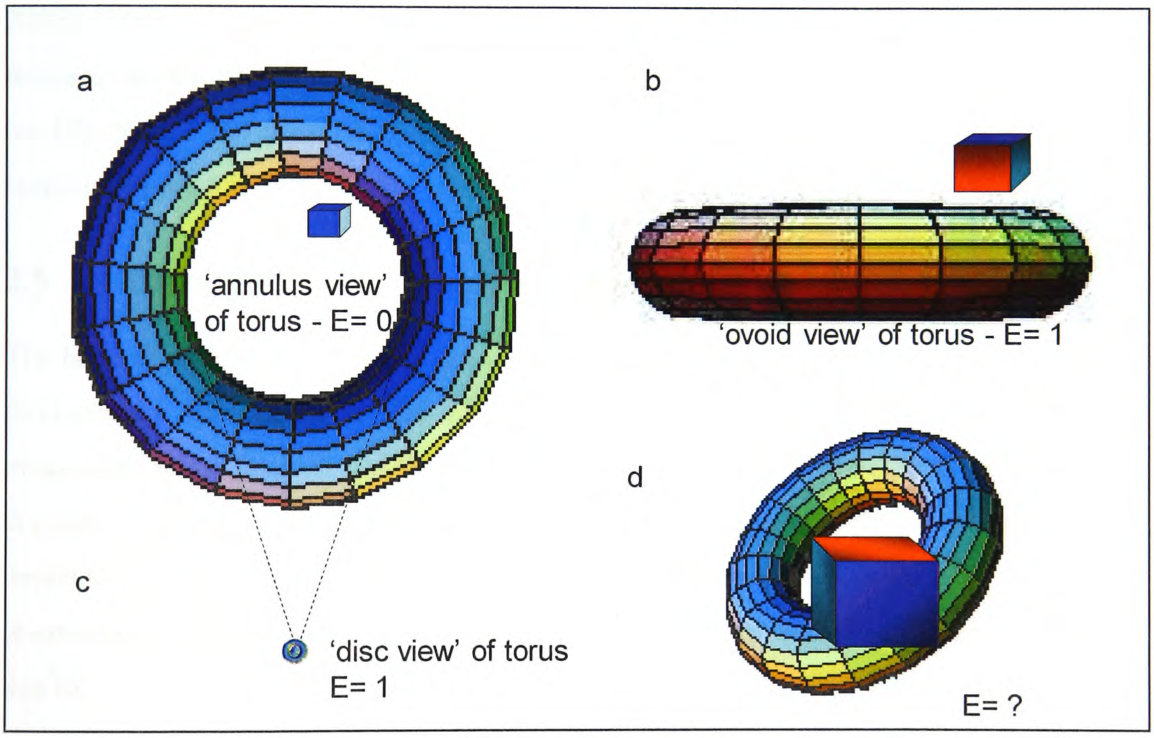

Figure 8 : Euler Character and view dependent occlusion: (a) Annulus view of torus with cube (b) Ovoid view of torus with cube (c) Disc view of torus (d) Torus partially occluded by cube

The fundamental issue in topology, establishing invariant properties under geometric distortion, remains true in what might be termed 'perspective topology' in the limited sense, and 'visual topology'[8] more completely. The effect of perspective can change the size or shape of an object but topologically it may remain the same. However unlike, for example, affine transformations (Laurini and Thompson 1999 p. 286) visual-topological invariance may only be true over some ranges of viewing position and angle. The torus, which has the outline of either an annulus or ovoid in perspective, would as far as the viewer is aware have an Euler number of 0 in Figure 8a, however the ovoid view of the torus visible in Figure 8b appears to have an Euler number of 1.

Visual topology is distinguished from perspective topology by considering that which can be seen given the optical characteristics of the atmosphere (or presentation medium) and the limitations of the human eye (Hinckley, Tufts et al. 1996; Ogburn 2006). Such optical characteristics introduce a limit as to the distance at which features are resolvable, thus at great distance a torus may appear to be a solid disc as per Figure 8c[9]. The question, to which this section is addressed, is how to describe the scene in Figure 8d?

2.5 Topology, accuracy and visual attenuation

The issue of whether or not a topological feature is resolvable visually reflects a more fundamental link between the identification of topological characteristics and measurements of geometry. Although topology is usually considered in an infinitely divisible Euclidean space, in practice whether or not a topological connection exists depends on our ability to discriminate between the objects or parts of objects (elements). This introduces uncertainty as to when a topological relationship exists due to:

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[8] The author is not aware of any previous attempts to formally describe the visually apparent topology of objects by their apparent Euler number. Lieztmann Lietzmann, W. (1969). "*Visual Topology*, Chatto and Windus, London.". uses the term, but only in reference to the books employment of graphical examples to illustrate topology in general.

[9] Alternatively the distance-scaled view of the ring may become so thin that the object cannot be seen at all.

- Measurement error - when transforming a real world object to a computer representation e.g. (Veregin 1991).
- Minimum resolution of computer representation of objects – in particular due to the 'intersection point' of two lines potentially requiring higher accuracy than the co-ordinate system affords e.g.(Worboys 1995).

These need to be taken into account when studying topology in applied situations. They become more important when one does not have full knowledge of the objects but only information on how they appear to be linked from a given perspective within the model, as presented in a particular media and as seen by the observer. There are, therefore, three further stages through which a visualised topology must go, each with qualitatively different types of uncertainty:

- Error in internal representation at each stage of the graphic pipeline (Foley, van Dam et al. 1990).
- Uncertainty due to the linear intersections and multiple scales produced by perspective projection (Worboys 1995; Sang, Birnie et al. 2005).
- Error in External Representation e.g. screen resolution (Hinckley, Tufts et al. 1996).
- Error in External Perception e.g. limitations in human visual acuity (Lucas 1991; Morgan 2005; Ogburn 2006).

It is also arguable that for some purposes, such relationships are not errors in the modelling of our knowledge about objects, but valid representations of how those objects are to be understood. For example, when using visual route finding, if there is no apparent gap between two buildings until one is very close to them, that route is less likely to be used, something which would be important to include in applications such as crowd evacuation simulations.

2.6 Measuring multiple perspective Euler Characters

The Euler number was introduced, in Section 2, as describing the topological properties of an object, and it was shown that from different viewpoints the apparent visual Euler number could change. To understand the visual topology of an object, rather than asking 'what is the topological character' – the Euler characteristic, or Euler number (Griffiths 1976; Kinsey 1991) - of an object, one must ask 'how many distinct or unique topological characters' an object can appear to have from different perspectives. For example, a view of a torus from different angles of rotation will change the *apparent* topology, unlike a sphere which looks the same from any angle. It does however have definable topological regions within which the value doesn't change.

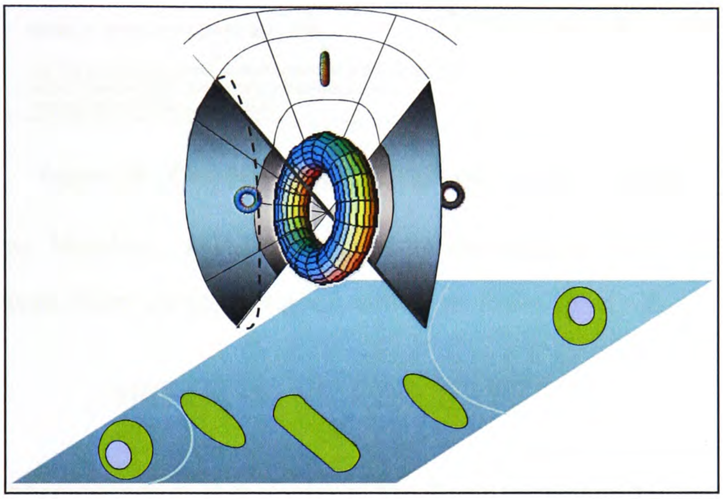

Figure 9 : Deriving Euler Zones

To gain a representative sample of the topological complexity of the torus in Figure 9, the viewpoints should be chosen such that from each it has a unique Euler number (En). To provide a net description of the topology as seen from these different regions, one could consider the mean or variance of the Euler number (Evar). This entails establishing the number of regions from which the torus appears to have a distinct topology. The region, termed an 'Euler Zone' (Ez) is the maximal contiguous, volume from which the same Euler number is visible and that is bounded by other regions with different Euler values. The sum of the Euler value in each zone can then be divided by the number of zones to provide a mean Euler value for the apparent visual complexity of the torus (Figure 10).

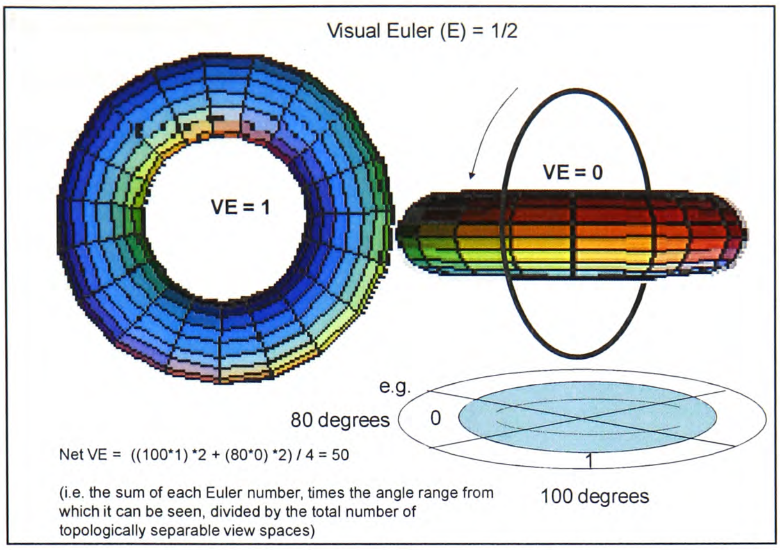

Figure 10 : Characterising Net Apparent Visual Topology

The 'Euler Zone Number', $n(E_z)$ is defined as the unique Euler value of the seen object from a given Euler Zone, or region within an Euler Zone - R.

Equation 4 $$n[R] = v_R - e_R + f_R - 2g_R : R \in E_z$$

[i.e. number *of* region R = (Euler's equation) *such that* R is an element of the Euler zone Ez]

The 'Euler Range' (E_r) is defined as the set of unique Euler values of the seen object when observed from all possible view points within a given region O.

Equation 5 $$ER[O] = \{x : [\exists E_z \in O : EN[E_z] = x]\}$$

[i.e. x has a value equal to the Euler number of a Euler Zone within the region O and the range is every x where this is the case.]

The 'Euler mean' (E_m) can therefore be calculated as the mean of the Euler numbers from each of the 'n' Euler Zones. However, since the Euler Zones are of varying volume (v), the mean likely topological complexity to be seen can be weighted by the relative volume, giving the Euler area weighted mean (E_{awm}).

Although independently derived, the Euler Zone is a special case of Plantinga and Dyer's (1990) viewpoint space partition (VSP) and its dual, the 'aspect graph'. The

VSP divides the viewing space whenever a topological event occurs. The Euler Zone only divides that space when such an event also changes the net topological complexity of the image, which may provide a rationale for using only a sub-set of the aspect-graph nodes to characterise a complicated scene. This E_{awm} provides an index of the most common visual Euler complexity and Euler Range gives the minimum bound to the set of Euler values which it is possible to see. However, the upper bound is only theoretical, since there are an infinite number of viewing positions which could potentially provide a new value[10].

2.7 Potential applications

A point of common debate in the field of landscape preference research is the selection of locations to use as viewpoints over a landscape of interest. How does one achieve reliable visual indicators about areas with multiple, complex, types of landscape when only a limited number of views of each landscape can feasibly be shown to survey respondents? (Appleton and Lovett 2005; Sang, Ode et al. 2008).

By deriving the Euler characteristic of landscape regions from different viewpoints, the zones between which the characteristics are different can be delimited. Within each of these zones, the topological relationships between the land cover types will be the same, so geometric complexity will only change in a continuous manner - allowing estimates of mean and variance to be derived. One viewpoint in each Euler zone could, therefore, be considered a minimum representation of the range of views onto the landscape in terms of large scale features. The continuous variance in geometric landscape indicators arising from different locations within each Euler zone could then be statistically described to provide an estimate of how representative the viewpoint chosen for preference analysis is of that zone.

The Euler characteristics may themselves be useful variables in studies of landscape

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[10] Plantinga and Dyer Plantinga, H. and C. Dyer (1990). "Visibility Occlusion and the Aspect Graph, *International Journal of Computer Vision*, 5, 2, pp 136 – 160.".give an upper bound for the number of nodes in the VSP of $O(n^6)$ assuming full knowledge of the dataset, but for a landscape involving hundreds of thousands of vertices (or even more), most of which could potentially form horizons, this is effectively a theoretical limit, since the practical limit which can be investigated is far lower.

preference. For example, views of mountains are believed to be evocative of positive preference scores (ARRIAZA, CAÑAS-ORTEGA et al. 2004), as the layers of horizons add a sense of mystery to the landscape. Raising preference provided in this situation is also depth of view (e.g. along a valley) to retain the sense of exploration (Kaplan and Kaplan 1989). Euler's graph theory can be used to calculate Euler characters for views relevant to both of these problems.

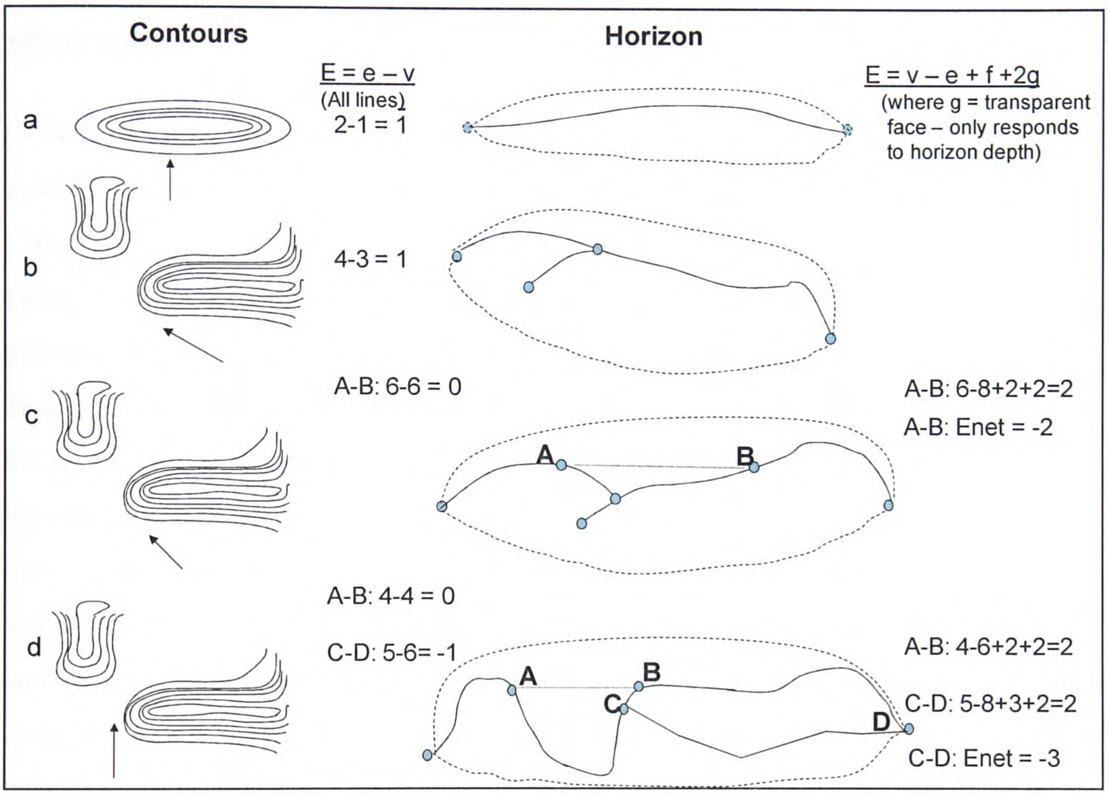

Figure 11 : Euler Graphs and Horizon Complexity

Figure 11a shows the Euler calculation for a simple horizon, which has an Euler value of '1'. Figure 11b shows a more complex arrangement of terrain with a viewing angle such that no 'v-shape' intersections of horizons are visible therefore, without any loops, the Euler number remains '1'. As the angle of view is changed, the v-intersect of horizons becomes apparent (Figure 11c), through which is visible a more distant horizon, line AB. Since line AB closes a loop, the Euler number becomes '0'[11]. Had

[11]Line AB may be either another part of the surface, or a designated "horizon line" – we suggest the convex hull of the surface, which would enable identification of such depressions in the apparent horizon surface as valleys by creating a loop in the horizon graph with a "transparent face".

there been no more distant horizon (and so no depth of view change) the Euler number would have been unaffected. As the position of the viewpoint moves into alignment with the centreline of the valley the 'v' shape will eventually disappear (Figure 11d). However, this will not influence the 'framing' (Lucas 1991) of the horizon beyond, nor will it influence the Euler number. For each additional horizon the Euler number will fall by one unit. Topology can therefore be used to predict some geometric characteristics such as variety in depth of the view and framing effects without directly measuring them.

In more complex terrain, loops may exist due to the presence of features (e.g. field boundaries, forest stands) and not due to changes in depth of view, (Figure 11d, line C-D). As this is qualitatively different it needs to be separately identifiable. By closing the graph to provide faces (the dashed lines in Figure 11), and re-defining the genus number in the Euler-Poincare formula such that 'holes' are transparent faces[12], through which more distant parts of that manifold can be seen, rather than handles in the manifold, a similar measure is obtained. In this case the Euler number increases by two per transparent face but not per non-transparent face. Therefore, Euler's network and surface formulae can be used in conjunction to describe landscape topology, or combined as a net descriptor (Enet) of the topological complexity which can be seen from a particular viewpoint. For example equation 6 would weight a change in depth of view as twice as significant than an additional landscape patch, see also 'Enet' Figure 11d.

Equation 6 $$((v-e) + ((v- e +f+2g) / 2)) - (v- e +f+2g) = Enet$$

Graph theory can be used to give a measure of how complex a view is in terms of the number of occlusions due to landform, and their concomitantly separate depths of view. Hence the Euler character is a crude, but viewpoint stable, indicator of visual complexity (Ode, Hägerhäll et al. 2010). A measure of occlusion should be indicative of preference due to mystery, for which Baldwin (1997) and the survey results

[12]A loop with one edge being not physically adjacent to the other elements must constitute a face with depth of view change.

presented in Section 5 provide some support. Ultimately, Euler zones could be used to stratify relevant sampling points for landscape preference studies, providing maps of the topological complexity which would be experienced when moving through that landscape, and units within which landscape characteristics are statistically tractable.

2.8 Dynamic visual topological complexity

The intersect characteristics visible from different viewpoints can be modelled as functions of their respective co-ordinates. In a landscape context this could provide a model from which to derive paths with maximum or minimum rates of complexity in topological change.

For example, when planning a footpath the designer would be interested in both the visual preferences of views from the path, and the ease of navigation. If the visual topology is too simple the route risks being uninteresting, too complex and it is difficult to navigate. The same is true for the larger landscape. Too simple and the view is both uninteresting and lacking in navigation features (Lucas 1991), too complex and the relevant route markers may be hard to find. But the dynamic aspect is also important since, at walking speed, more complex visual topology may form an interesting landscape but at driving speeds be disorienting (Lucas 1991). This raises interesting issues for future research, such as what is the significance for road safety and tourist route design of the rate at which topological events occur, i.e. the rate at which views switch between close and far, narrow and panoramic?

2.9 Conclusions

Given the range of benefits which have derived from other branches of study into the idea of topology, the concepts developed in this thesis could have wide ranging application. Some such applications have been suggested here, others may be contributions to visual knowledge encoding (Laurini and Thompson 1999 p.651), or the semantic understanding of landscapes (Mark and Turk 2003), leading to practical benefits such as supplementing GPS co-ordinates with anticipated landscape information. This section has set out the principles; however there are many questions to be researched before they can be directly applied.

In the field of landscape research, robust sampling of the landscape to describe its topology is a critical issue. The Euler Zone may present an objective means to limit the selection of scenes for landscape preference research, but work is needed to better understand the cognitive significance of different kinds of topological complexity in the landscape. Section 5 will make a start to this, but it may be for example that the VSP can be generalised in some other cognitively significant way. Visual topology provides richer information than standard visibility maps, but is technically more challenging to achieve. Sections 3 and 4 consider some of the methodological problems and propose some solutions but perspective GIS is already starting to prove useful in new mobile technologies (Tsaia, Leeb et al. 2012)[13], so the ability to deliver visual topological analysis to small mobile devices may be the critical development that is required to exploit the idea in its most natural context.

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[13] For examples see : http://www.esri.com/news/arcuser/0311/files/arandgis.pdf ; http://mashable.com/2009/12/05/augmented-reality-iphone/

3 Section 3 - From visibility analysis to view analysis : Improving GIS capability for visual problem solving.

3.1 Introduction

Visualising, and analysing a visual digital landscape (visual analysis) are two different operations that are often assumed to be technically interchangeable. Visual analysis is often far more demanding and for this reason, long established techniques in visualisation have yet to be taken up for scientific analysis purposes. Despite some core commonality in the need to handle perspective and hidden surface removal, computer graphics and visibility analysis continue to apply the techniques developed in their respective fields – computer science (the standard graphic pipeline) and geography/GIS (ray tracing). Historically, ray tracing methods were too slow for computer game graphics and could only be used for image rendering in small datasets (Shirley, Sung et al. 2008) whilst the perspective mathematics involved in the graphics pipeline made that a gilt-edged solution for analyses in GIS which sought only to establish "whether.. and possibly 'how much of' [an object] is visible" (De Floriani and Magillo 2003 p. 709) not what it looks like. Despite advancing computational power which blurs this distinction (Shirley, Sung et al. 2008), the difference has persisted. Fundamentally GIS users did not see the need for employing the methods from computer graphics. This was partly because the use of GIS based visual analysis was largely restricted to those who were aware of and could work within its limitations (for example Fisher (1994)), a fact which was both advantageous in ensuring valid use of the techniques, but perhaps also self limiting in that questions were restricted to those aspects for which technical solutions were readily available.

The explosion of GI related data and tools in the last decade has led to new questions being asked of geo-data by a broader range of people (the democratisation (Boulos and Burden 2007) or 'google-isation' (Infield 2009) of GIS). Computer graphics have become a mature, easy to use, technology. It has become possible for people to quickly access 3D visualisations of their world. It is relatively cheap to provide models of what it might look like in the future, be that due to climate change or a housing development. Indeed, most of the processes could be undertaken automatically, by uploading the architectural plans or a rendered model directly to online virtual worlds which automatically pull other relevant data together. As a result, geography has indeed become 'naïve' (Egenhoffer and Mark 1995), in the sense that once integrated with other technology analytical nuance in query design is lost and the required expertise for understanding results is less apparent when data is interpreted via intuitive visualisation.

As was noted in Section 1, what has not been developed so far is the means to ensure that the data itself, as well as the technical and SDI processes through which it is transformed, are fit for purpose. Nor has the technical potential to handle 'naïve' queries which Egenhoffer and Mark called for (Egenhoffer and Mark 1995) been realised in the 'virtual world' (Boulos and Burden 2007) context. For example, the ability to handle topological and spatial order queries (Egenhoffer 1989) in perspective, would allow for more efficient handling of Environmental Impact Assessments where human time per case is limited (Vanderhaegen and Muro 2005).

Section 2 set out some new theoretical ideas the author believes are necessary to begin to draw these lines of research together by considering perspective views not as dumb images but topologically connected layers of data. This thesis explores a technical solution to implementing these ideas. As such it first reviews the existing techniques from the fields of GIS and computer graphics as to their potential and limitations in providing the qualitatively rich visual analysis the new 'virtual world' requires. It then introduces a new method of encoding visually apparent relationships into terrain models which, although developed primarily with landscape analysis in mind, could have wider applicability.

3.2 Traditional GIS visibility analysis

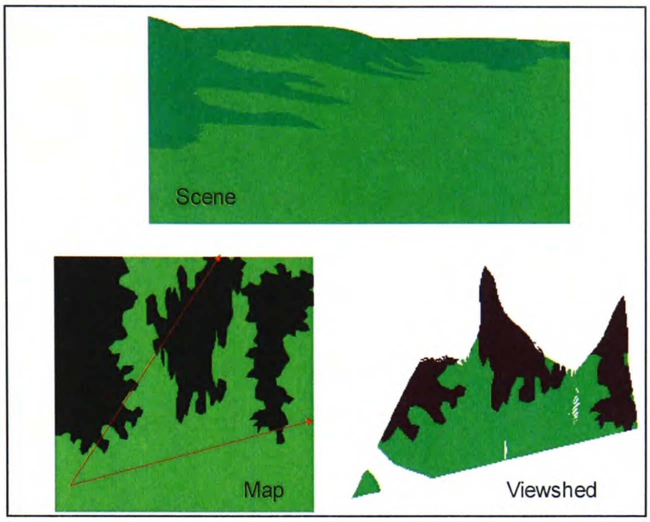

Figure 12 : A Computer Generated Scene and the corresponding map and viewshed.

Viewshed mapping (Figure 12) is the process of delineating on a map the areas which can or cannot be seen from a particular location. Two basic processes are commonly available for determining occluded areas; ray tracing (Watt 2002) where a line of sight is established between two points on the Digital Elevation Model (DEM); and segment comparison (Madern, Fort et al. 2007) whereby objects from the model are projected against a virtual image screen, the more distant being projected earlier and by some means intersected or over written by later objects. The latter is rarely used in GIS however (one example being Madern (2007)), primarily because the raster format of most DEM makes ray tracing relatively efficient and simple. Other visibility analyses are discussed in Section 3, but a fundamental reason for the popularity of ray tracing in GIS is the ease with which the result may be summarised on a map. A viewshed (Figure 12) provides a summary of a key variable (visibility) that is tractable to spatial and statistical analysis (particularly statistics such as visible area on *other* map layers). This allows pursuit of objective measures and analytical summation in a way that perspective views do not. But the technique has two key limitations. Firstly it does not provide the view, key details such as apparent landform are missing and the visible area may have holes and islands because 'no-data' values represent occluded surface. Secondly the method is suited to, and usually implemented as, a global approach (i.e. 360 degree panorama) rather than being built as a landscape is explored, but this implies analysing all data (before knowing whether it is of interest to the task or not) with what is a time-linear process at best (Reif and Sen 1988). Both these aspects reduce its utility for the new, dynamic, integrated GIS of visualizations and mobile applications. Visibility maps take this a stage further by considering how many other locations can see a particular location. This is repeated for all possible locations providing a map of visibility, and a computationally $O(n^2)$ problem (O'Sullivan and Turner 2001). Dynamic mapping of the viewshed from a moving location, or from many stationary locations simultaneously represents a problem with complexity falling between these two bounds, depending on the number of viewpoints.

General or Discrete Mesh Simplification (Leubke, Reddy et al. 2002 p.9), as opposed to viewpoint dependent simplification (see below), is the most direct means to speed up viewshed analysis as the Level Of Detail (LOD) is pre-processed. However, generalising the terrain can have significant impacts on the viewshed for each viewpoint (Fisher 1994), so is usually to be counseled against other than by some form of variable resolution TIN, e.g. Puppo (1996), or quad tree, e.g. Pajarola et al. (2002), structure to reduce the number of cells to be considered in very homogeneous areas of the dataset, such as open plains. Alternatively, a subset of the terrain might be used as viewpoint cells but maintaining the original terrain resolution for testing occlusion (Miller and Law 1997), this reduces the chance of a minor generalisation in the terrain producing a significant error in each viewshed, although the visibility map is only available at the lower resolution.

The other key approach to improving speed is pre-calculation of the visibility map. Operations using visibility as an input mask to determine relevant other information might pre-prepare visibility maps that will be used many times. Planners involved in Environmental Impact Assessment (EC 1997) might wish to pre-prepare a map of the region that can be seen from residential areas, so proposals in such regions can be quickly identified as relevant to those residents without computing the information each time. O'Sullivan and Turner (2001) take this further[14], suggesting that rather than compute a net inter-visibility, the viewshed be calculated for each view point and stored in a matrix (each row being one view point, and each column possible other locations marked visible or not). Visibility maps can therefore be quickly calculated for any column without repeating the ray tracing operation. As O'Sullivan and Turner (2001) recognise however, pre-calculating the view-shed or visibility map loses the spatial context so any change in the potentially occluding terrain would require every viewshed to be recalculated.

All of the techniques for ray tracing only improve the utility of GIS visibility analysis with respect to the issue of speed. While variants of ray tracing could be used to provide qualitatively richer information, such as potential development impact (Rød and Van Der Meer 2007) they do not provide an elegant solution for extracting information about what the scene looks like.

3.3 Techniques from computer graphics?

Visualisation, in terms of the simple representation of data in a perspective view, is also a standard process. Projection is mathematically well understood (Mortenson 1989) and implemented (Angell 1981) and hidden surface removal and rendering algorithms (Watt 2002) exist which are both efficient and accurate. They are, however, still quite slow given the frequency with which the operations must be repeated for a landscape, and being aimed at presentation, they don't usually retain the necessary information for analysis. Multiple-core processing may be extending the life of 'Moore's Law' (Shan 2006) but the data and process requirements are also increasing 'exponentially' (Shirley, Sung et al. 2008). To represent movement most applications employ some form of pre-processing to minimise the amount of data which needs to be visualised. Most often this takes the form of attempting to reduce the proportion of the original data which must be put through each stage of the graphics pipeline or pre-processing some of the stages. The key question for

[14]They credit De Floriani, L., P. Marzano, et al. (1994). "Line of sight communication on terrain models, *International Journal of Geographical Information Systems*, 8, pp. 329– 342.". with the first use of the idea in GIS.

landscape visualisation and analysis therefore, is how perspective views may be created and analysed without compromising scientific credibility and operational utility for landscape planning.

3.3.1 The Graphics Pipe-line

The stages between the underlying model and the visible output are often referred to as the 'graphics pipeline' (Watt 2002)[15].

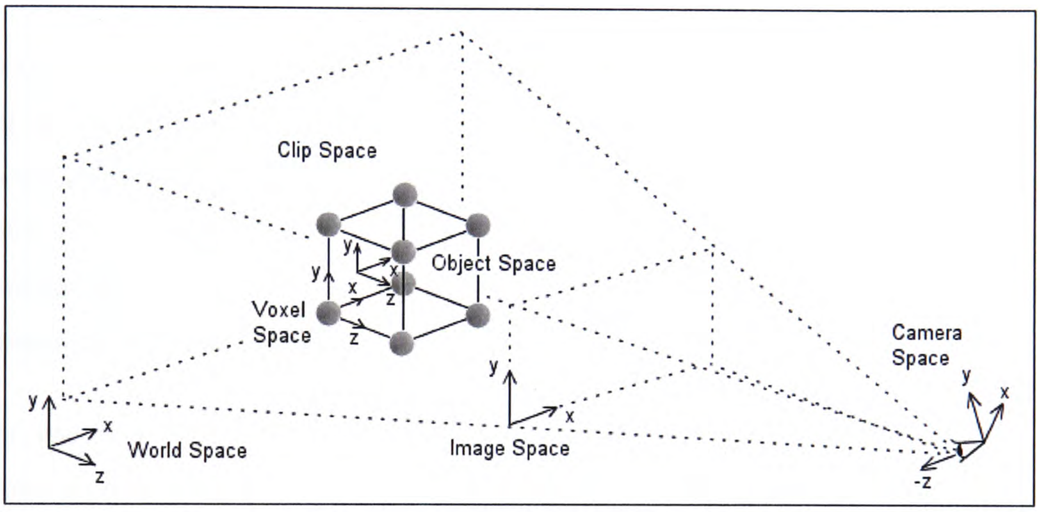

Figure 13 : Local, World and Camera Co-Ordinate Systems[16]

Although in modelling landform one is usually concerned with a single object, potentially other objects such as buildings or trees might be added to that scene. It is worth noting therefore that each object in a model may have its own origin and co-ordinate system, which must be transformed to a common 'world' co-ordinate system first ('world space', Figure 13). This world model includes the position of any light sources in the scene if relevant.

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[15]We consider a simple system as set out in Watt (2002, p.142), more advanced options such as PHIGS (Watt 2002, p.157) are considered unnecessary to convey the issues for this review, though the facility for programmatically efficient simultaneous viewpoints is a notable benefit.

[16] http://www.hyperzoid.com/csc492/rendering.html

3.3.2 Eye-View / Camera-view co-ordinate system

The eye-view co-ordinate system has its origin at the view point ('camera space', Figure 13). It consists of a viewing direction (z) and a view volume defined by the view plane at the maximum depth considered visible ('clip space', Figure 13) and planes between this and the view point at the maximum angle of view ('Θ', Figure 13). Objects in the world co-ordinate system must be transformed to this such that the depth of view falls along the z axis.

At this point the data can be thinned to remove those elements which will definitely not be visible. Back-face culling is simply the removal of all those elements which are facing away from the direction of view (as determined by their vector-normal (Watt 2002 p.12 and p.147). It will be shown that the same basic process can be simultaneously employed to identify potential horizons at this early stage allowing substantial efficiency savings.

The use of a view frame, or 'frustrum', limits the number of objects needing to be projected to only those in the angle of view. This is problematic in GIS where wider angles of view might be desired (up to 360°). Also difficult to employ in landscape analysis is the common graphical technique of using a 'far clip frame' – a plane beyond which any element is considered too small to be seen, since while attenuation of distinctiveness with distance is an important element for landscape visualisation (Turner 2003) using a clip frame may leave the topology of the remaining objects ambiguous (Leubke, Reddy et al. 2002), and maintaining smooth horizons then often necessitates techniques such as atmospheric fogging which may in fact be a variable of interest scientifically e.g. Bishop and Miller (2007). Viewpoint dependent mesh simplification (dealt with specifically later) would also take place at this stage to reduce the number of objects by more coarsely representing distant objects.

3.3.3 *Perspective View - Screen Space / Image Space*

Equation 7

$$f = \frac{w}{\tan(a)}$$

$$g = \frac{h}{\tan(b)}$$

$$S.x = \frac{P.x * f}{P.z} + \frac{w}{2}$$

$$S.y = \frac{P.y * f}{P.z} + \frac{h}{2}$$

w = display width, h = display height, a = horizontal angle of view, b = vertical angle of view, P.x = model co-ordinate, S.x = screen coordinate.[17]

Perspective projection involves simple trigonometric calculations (Equation set 7) to project a graphic element along a line running from the viewpoint, through the vertex of the object to the point at which it will intersect the 'screen'. In general the process is very accurate, and can be efficiently computed via a linear transformation matrix to avoid sequential trigonometric calculations (Carlbom and Paciorek 1978), and hardware implementations are common. However, because the length of the projection vector to a flat screen becomes near to infinite as it approaches 90 degrees to the view, broad viewing angles require a curved 'screen' against which to project

[17]This is based on and further explained in http://easyweb.easynet.co.uk/~mrmeanie/persp/persp.htm

objects. Curved projection screens are not generally supported by commercial graphic hardware so the benefit of hardware accelerated processing is harder to achieve making the process less attractive to those wishing to undertake 360 degree visibility mapping.

Two sources of error are particularly significant at this stage. Firstly, small errors in the source model cast large shadows onto more distant elements as their size is multiplied by a function of distance. Secondly, any floating point errors (due to there being a maximum resolution of any co-ordinate grid which perspective projections inevitably cut across (Worboys 1995 p.188)), will have a similarly magnified effect. In the worst case, this might be sufficient to create an error as to which object is nearer and which occluded during hidden surface removal (HSR).

3.3.4 HSR algorithms

HSR methods generally fall into two categories, object-space and image-space (Sammet 1990 p.267) depending on whether the decision as to 'what occludes what' is taken with regards to the objects in the model, or the geometry on the screen/image space.

One image space method, similar to GIS visibility analysis, is to run 'point in polygon' (Laurini and Thompson 1999, p. 537) operations to determine the sequence by which objects are intersected as a ray is traced from the eye to the 3D screen space. However the basic form is computationally expensive (that is the time constant per operation is large) as a ray must be traced to every screen pixel (Shirley, Sung et al. 2008). It is usually only employed for more complex rendering purposes such as partial transparency and shadow rendering or to enhance radiosity based illumination (Glassner 1989; Watt 2002 p.307; Shirley, Sung et al. 2008). For this reason, algorithms to speed up ray tracing are continually being developed (Watt 2002 p. 354-366; Shirley, Sung et al. 2008). Computer games for example may first use the storyline to limit the calculations needed to a sub-area of the screen at any one time. Predictable scene change allows hierarchies of bounding volumes (Watt 2002 p.357) to be used as a prior test for ray intersections leading to a detailed ray trace for particular objects only when their bounding volume is intersected. Scene coherence (Watt 2002 p.358) may also be used to allow a lower sampling ratio of ray traces in some areas. These efficiencies pose difficult ethical and practical problems for landscape analysis however. One of the key drivers for developing virtual worlds is in order to avoid pre-determination of what routes are followed, and allow flexibility in changes made to the model. Scene-coherence is also a variable of scientific interest (Gibson 1986; Appleton 1996), so correlation of this with rendering accuracy or performance would be a questionable approach.

HSR is also frequently achieved via the 'painters algorithm' (Sammet 1990 p.271) whereby the screen is simply updated from background to foreground, thus occluded objects are painted over. Each object is ordered in the z dimension and progressively intersected with nearer objects, producing a surface of non-occluded 'cels'[18]. It has the advantage of being 'acyclic', objects are already divided in to 'cels' so avoiding the problem of what order to draw three elements [a,b,c] when [a] occludes [b], which in turn occludes [c], and [c] then occludes [a] (as per Figure 14). It also, however, produces a 'dumb' image where each layer painted is entirely unaware of what objects its colours represent and what objects it is painting over.

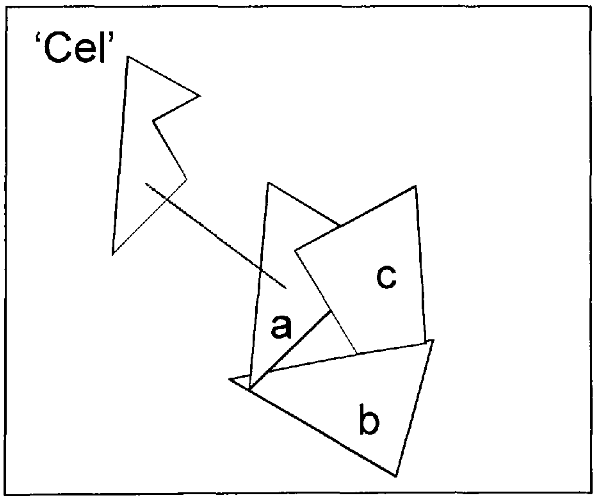

Figure 14 : Cyclic occlusion.

[18]The spelling 'cel' is used to refer specifically to this concept and should not be confused as a miss-spelling of 'cell', the more generic term for a discrete unit.

Image coherence may be used to speed up the rendering process (as opposed to scene coherence that excludes objects prior to rendering), by applying a quad-tree to the output and aggregating those 'cels' with the same value (as per Warnock's algorithm (Sammet 1990 p. 272), but even given the previous methodological caveat, this is only an efficiency saving after the most costly process (visibility analysis) has occurred.

Object-Space HSR provides the opportunity for some efficiency savings in advance. Samet (1990) provides the Weiler-Atherton algorithm as a typical option: polygons are ordered as to their nearest z value and projected, those whose projected shadows fall within the shadow of the nearest object are marked for occlusion or clipped if partially visible, and the process repeats for the next element not already occluded. Again, every element must at some point be projected and compared for occlusion, however there have been methods proposed to reduce the number of visibility operations needed when a viewpoint changes. Fuchs, Abran and Grant provide an early example of using a Binary Space Partition (BSP) (see Samet 1990 (Reif and Sen 1988; Sammet 1990 p.283) to provide some prediction as to areas of visibility. The BSP works by selecting a polygon, and dividing the entire dataset by the plane on which it lies (a polygon intersecting that plane would be represented in both branches). The process is repeated for each branch building up a binary tree. Assuming there is some coherence to the object-space, this will divide the space into regions of elements either side of particular planes. HSR is then achieved by visiting first those nodes of the tree which do not fall within the same partition as the view point, providing scene ordering, so a painter's algorithm may be applied for each new view, without having to calculate proximity to the view point for every polygon each time. Reif and Sen (1988) go further by projecting the horizon against the tree. If it does not spatially intersect higher nodes in the tree, the lower elements can be ignored, reducing the number of intersections that must be computed. Aspects of the BSP technique hold some promise for dynamic landscape visualisation, however it faces two problems. Firstly, time saved depends on the efficiency of the tree for a particular view point, suggesting some story management would be required. Secondly it assumes a stable scene which does not itself change otherwise the tree must be reconstructed.

Dynamic scene change is better served by the 'z-buffer' approach (Shirley, Sung et al. 2008). A z buffer is simply an array or 'virtual screen' that holds information as to both colour/hue and z view-depth for each pixel. If a change in the scene occurs it can be projected straight to the z buffer, which will only update if the new z value is closer to the view point than its current value. The z buffer is fast, because it can be implemented within dedicated graphics hardware that is commonly available (Shirley et al. 2008), for this reason it was employed by Bishop et al. (2000) as a means to quickly generate depth-of-view metrics. However it holds only information on colour and depth. Potentially a CPU-driven z buffer can also hold classification information, but the link with the original data has still been broken. Any dynamic feedback of information between the z buffer and a land cover change model would need to be handled as parallel processes[19]. The issue of disconnecting perspective objects from the original data is a fundamental limitation of all the HSR methods considered so far in regards to their application to landscape analysis.

3.3.5 View space

The view space is simply the area of the computer screen onto which the image is presented. This involves a final co-ordinate transformation to the image space (Figure 13) origin, and proportionally re-sizing of the window's dimensions to match the display screen. Here too however, the process may result in changes to the apparent data that via pixilation of the image may alter the apparent topology between different elements or exclude small features entirely. Properties of the screen are also analogous to the eye's retina in that both have a finite (but different) ability to discriminate by size, luminance and hue (Ogburn 2006) (Leubke, Reddy et al. 2002 p. 239-278), information which needs to be modelled if the aim is to simulate human

[19]Weghorst et al.Weghorst, H., G. Coppoer, et al. (1984). "Improved computational methods for ray tracing, *ACM Transactions on Graphics*, 11, 2, pp 214-222."., see Watt Watt, A. (2002). "*3D Computer Graphics 3rd Edition*, Addison-Wesley, New York."., suggest speeding up ray tracing by adapting the z buffer to provide pointers to the visible objects at each pixel. This could be adapted to use the image plane topology as a link across occluding boundaries. However it would entail maintaining a parallel data structure of pointers which, without intelligent processing of the scene, would be an expensive heuristic – one pointer per cel per viewpoint.

vision within a computer (Leubke, Reddy et al. 2002 p.239) or evaluate potential error sources within presented material in different media.

3.3.6 View point dependent mesh simplification / Level of Detail

Since both the human eye and the computer have increasing difficulty discriminating between units as they become more distant to the view point and as contrast declines (Levine 1985 p.110; Leubke, Reddy et al. 2002; Ogburn 2006 p.245), simplifying the dataset on the far horizon can both save computation time and, arguably, improve the simulation of human vision. View point dependent LOD (as distinct from global LOD in GIS) aims to generalise the mesh (usually in TIN) by some function of distance to the view point (Leubke, Reddy et al. 2002 p.10). This is important in establishing the LOD required to compute topology (Leubke, Reddy et al. 2002 p.16), and may result in a different mapping between foreground and background than might be the case otherwise. Its utility for visibility mapping may be limited as re-computing a temporarily generalised mesh for every location would be a substantial overhead.

One aspect of computer games technology which might help would be varying the LOD by whether the general location is visible or not. By this method the whole model is only loaded in at a very coarse level of detail. Only those areas which are visible are loaded in at the higher resolution (continuous LOD (Leubke, Reddy et al. 2002 p.10)) via a nested space partition (Leubke, Reddy et al. 2002p. 190). The result is not, of course, a complete visibility map, but if the starting premise is to support dynamic applications, it would be applicable for making a visibility map which grew in terms of detail as areas are visited more closely. In addition to computation savings an LOD based topology could provide a new representational variable e.g. the degree of LOD reduction could be altered to simulate different levels of eyesight quality or atmospheric dust. However, the concerns of Fisher (1994) should be addressed for any reduction in DEM that might affect occluding horizons.

3.4 Landscape analysis and the graphics pipeline

3.4.1 Speed and accuracy

Many of the current algorithms for projection and HSR are only sufficiently fast for dynamic display if processes of generalisation in geometry, spatial structure or attribute information are employed (Leubke, Reddy et al. 2002 p.174). It has been argued here that these generalisations are potentially problematic for use in landscape analysis. A more fundamental problem to the graphic pipeline approach in the context of landscape analysis is that the simple presentation of the data in perspective view is not sufficient. Analysing the apparent arrangement of land cover involves retaining some information on what the points, lines or areas of colour projected on the screen actually represent. Firstly, working back from the projected image to the data is time consuming and hard to automate (Sang, Ode et al. 2005) and graphics card-based HSR algorithms do not retain this information. Secondly, to be able to take into account geographical context (for example to test one component of Kaplan and Kaplan's (1989) theory of landscape mystery – that people subconsciously predict occluded landscape features), requires either complex parallel processing of the scene and map data, or retaining a topological link between the visible area (the viewshed (Burrough and McDonnell 1998 p.200)) and the non-visible areas. It also involves discerning the topological links between objects that are adjacent in the perspective view but physically separate in the map, something that existing algorithms are unable to do.

However, landscape analysis as an application also provides options for efficiency savings. One can assume that, unless the terrain were to contain tunnels or bridges[20], by scanning the mesh from the view point outwards, any object with the same x co-ordinate in *screen* space as a previously projected object, and lower screen space y co-

[20] If there are tunnels, a simple additional operation can be employed to establish visibility. If the point is found to be below an existing line, one can check whether the area in the view below that horizon is solid by querying the vector normal of the potentially occluding triangle's neighbour. If it is groundward, the horizon must be the edge of a tunnel or depression. However for now the simpler case will be assumed.

ordinate, must be occluded (as recently expounded from object graphics to GIS visibility analysis by Madern et al. (2007)). Most of the cost of visibility analysis is in the intersection testing (Watt 2002 p. 355). If the geometry is not the cels of the mesh but rather each cels' bounding edge, intersect testing can be avoided except for edges which after approximate testing via the end nodes, might still intersect the current horizon.

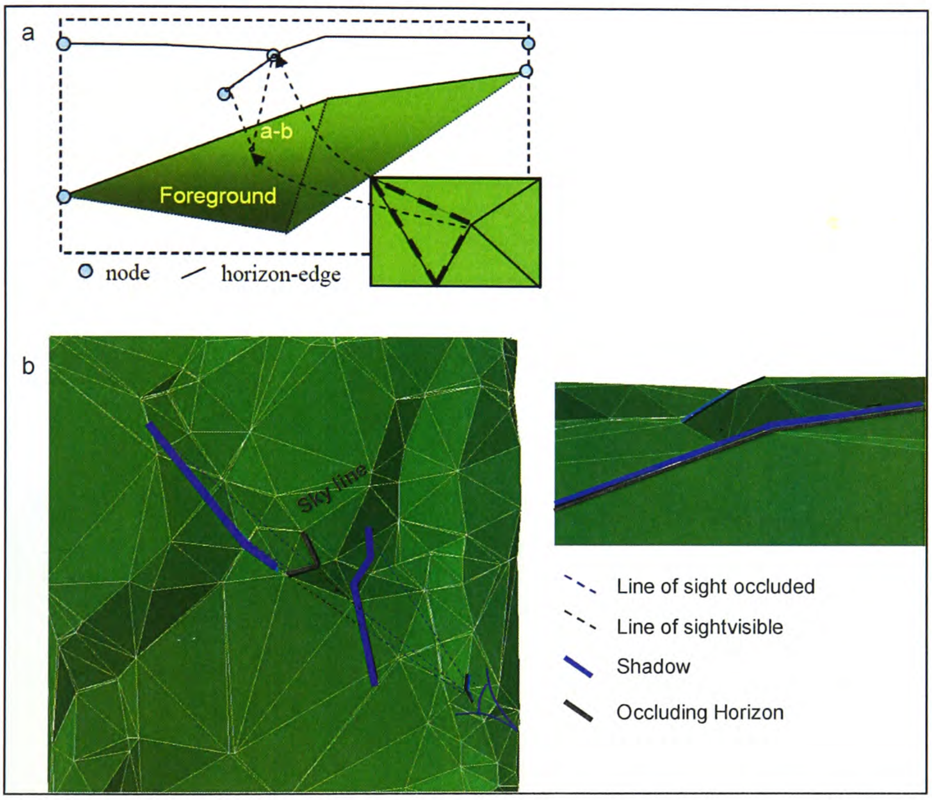

Figure 15 : (a) Maintaining a current horizon for Hidden Surface Removal and (b) the resulting information in orthographic and perspective views

For example the dashed lines in Figure 15a represent one cel to be so tested. The shaded triangles in Figure 15a represent foreground which has already been projected. One edge of the test cel has two nodes both visible and thus no further processing is required, but the dashed line a-b has one node falling below the horizon of the foreground. This line must be intersected with the occluding horizon to determine where the occlusion occurs.

Having established that to calculate visibility, one need only be interested in relationships around the current horizon, it should be an obvious step to note that it is the relationship between occluding horizons and the surface they partially occlude which is of interest. A map of the visible horizon edges, and the edges on which their shadows fall, completely describes the visibility of the land surface in between. So, rather than holding a viewshed as a separate layer, one could incorporate this horizon and shadow information as attributes of the DEM (or a layer draped over it). To determine visibility at any given point, one simply establishes if the first line intersected between that point and the view point is an occluding horizon, if so, the point is occluded, else it is visible. For example the dashed lines in Figure 15b, show the line of sight across a DEM, coloured blue when the land over which they run is visible, black when occluded. The solid lines represent the occluding horizons and the shadows they cast.

3.4.2 Visual fields: variance in view analyses

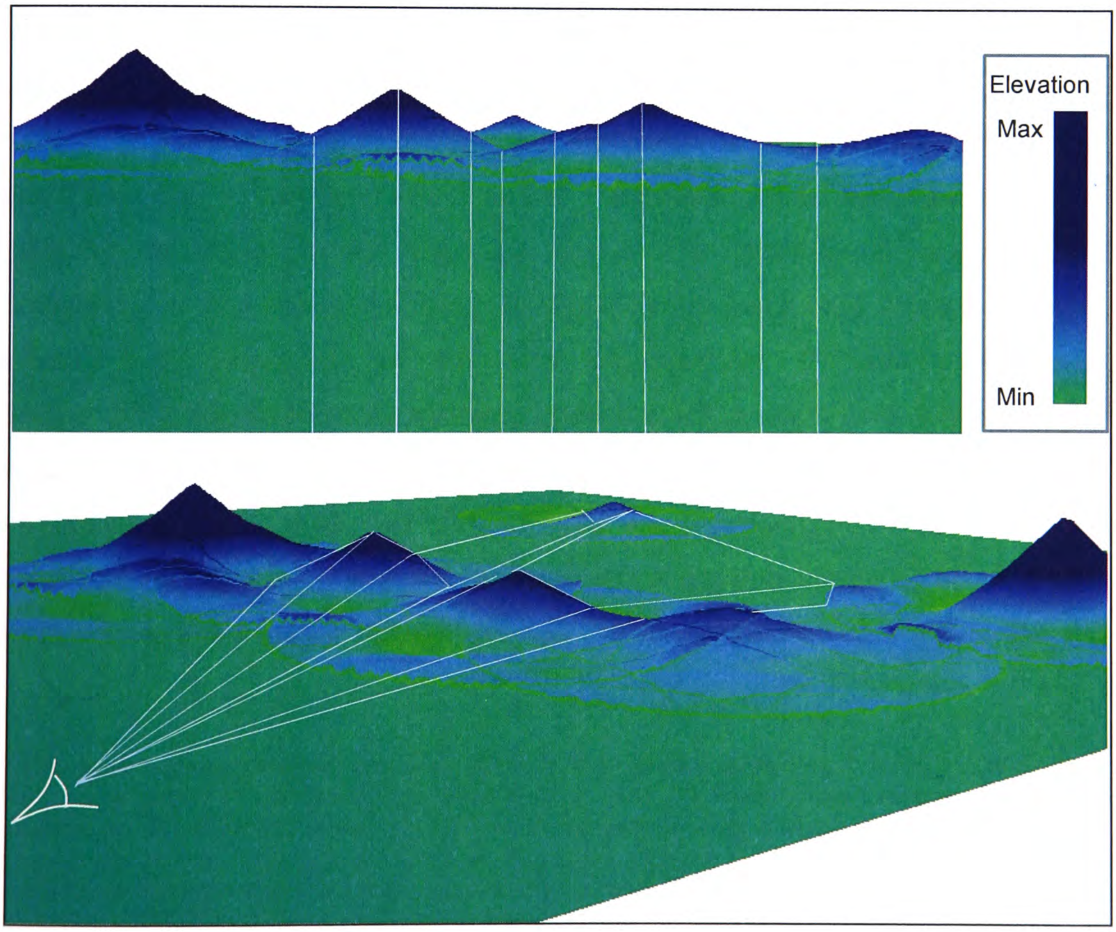

Figure 16 : (a) Lines of sight to topological events in the scene and (b) the 'visual hull' they form spatially.

Figure 16a shows the lines of sight for depth of view changes at intersections in the horizon graph, while Figure 16b provides a side view. From this angle it is possible to see how the lines of sight form a polygon or 'visual hull'[21], which is a special case of a visual field. The concept of visual fields was first noted by Cova and Goodchild (2002) as a special case of field-objects (Worboys 1995). They present a range of generic examples of the application of field-objects, such as network path optimisation, and identifying location correlations in model sensitivity. In particular Cova and Goodchild (2002) note the use of field-objects to provide a greater insight into the range of options, whereby near-optimal solutions are also available rather than only the optimal solution. In a visual context, for example the field might provide a geometry against which to test difference in degree of visibility rather than rely on a simple binary answer.

It is this ability to investigate near optimal solutions which also distinguishes the visibility-graph (O'Sullivan and Turner 2001) from a standard viewshed analysis. Since the visibility graph represents all the viewsheds simultaneously as a matrix, variance in visibility within sub-regions of that matrix is also searchable (O'Sullivan and Turner 2001). However O'Sullivan and Turner (2001) note that a key problem is selecting the objects in the landscape for which to construct the graph. They recognise that "the space complexity of this visibility graph data structure is $O(kn)$ where k is the average size of each vertex neighbourhood" (O'Sullivan and Turner 2001 p .226). Significantly, the visibility graph is purely a topological field-object. As a result it has no means by which to "reverse the process of visibility graph construction - that is, many sets of locations in many environments could produce the same visibility graph, so that the environment so represented cannot be recovered from the visibility graph" (O'Sullivan and Turner 2001). This also means that the

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[21]This is not the same use of the term as that defined by Laurentini Laurentini, A. (1991). "The visual hull: A new tool for contourbased image understanding. *Proc. 7th Scandinavian Conference on Image Analysis*, pp. 993-1002.". in respect of visual object recognition which is based on the silhouette projection of an entire object, not its self-occluding boundaries. We use the term in reference to its similarity to the convex hull, that being a commonly understood concept in computational geometry Skiena, S. (1998). "*The Algorithm Design Manual*, Springer-Verlag, New York, USA. ." and GIS Wright, M., A. Fitzgibbon, et al. (1996). "Convex hulls, occluding contours, aspect graphs and the Hough transform, *Image and Vision Computing*, 14, 8, pp 627-634.", Laurini, R. and D. Thompson (1999). "*Fundamentals of Spatial Information Systems*, Academic Press, London."..

process cannot be locally updated to detect, or take into account, changes to a visual field due to altered geometry in the landscape, nor describe and detect lateral visual topological relationships.

Taking the concept of the visual field (Cova and Goodchild 2002) to that of a full geometrical object in the landscape would allow line-of-sight and apparent lateral topology to be queried by traversing the edges of the visual field-object as this would connect the landscape along lines-of-sight.

Local changes could be detected by establishing if they are within a visual field-object's volume. The visual hull in Figure 16 therefore could provide an object akin to a bounding box (Laurini and Thompson 1999 p.126) or view point dependent convex hull (Wright, Fitzgibbon et al. 1996), as a preliminary test geometry to establish if a change requires a new visibility analysis.

Dynamically managing topology in 'spaghetti' vector format would be computationally expensive (Haines 1994). For raster representations, the multiple scales and cross-axial vectors inherent in perspective operations could be problematic also, requiring some form of quad-tree representation (Worboys 1995) to provide the higher resolution needed in some areas. Efficiency of storage and query becomes especially important if fuzzy viewsheds are of interest (Fisher 1994; Ogburn 2006). Having established the potential benefit of managing the topology of visual relationships, the question is therefore whether it can be effectively implemented? A reasonable definition of effective would seem to be whether or not the implementation can support visual analysis for Environmental Impact Assessment as set out in Section 1:

a) To support processes foremost: integration; visualisation; and dynamic update.
b) Metrics need to be available by individual view. However, they must also provide the option for widening the spatial information to masked areas of the scene.
c) To provide summary metrics of landscape change.
d) Metrics need to be dynamically calculable along individual path choices.
e) Metrics are needed to determine how representative viewpoints (selected for presentation) are of the possible range of views onto and within an area.

f) Metrics need to provide information on the robustness of data for representing the view from a particular view point, including issues of visualised vs. map scale, and data heterogeneity within partially visible spatial units.
g) An SDI must provide the possibility to optimise between visually robust units and other demands in statistical unit design.

These have three basic technical requirements in common, the ability to establish:

i) How occluding horizons link together in perspective view.
ii) Which parts of the landscape are visible immediately beyond such horizons.
iii) How (i) and (ii) change for changes in the model or viewpoint.

3.5 Visual Topology – Choice of implementation in Quad-Edge TIN

There are two forms of visual topology, inter-visibility (along lines of sight as per a visibility graph) and 'lateral topology' (which elements appear to be next to each other from a given perspective). The former was efficiently recorded by O'Sullivan and Turner (2001) but was not updatable. The latter has so far only been recognized as a property of the view in the field of Machine Vision (Plantinga and Dyer 1990) and only been accessible by post-hoc image analysis (e.g. via e-Cognition (Definiens 2011) or manually (e.g. Germino *et al.* (2001); Sang *et al.* (2005; Sang, Ode et al. 2008)) which is both a slow process and also not easily updated. Both problems arise from the fact that the visibility information has been removed from its spatial context. They are also both, however mediated by the same elements – horizons and their shadows. Rather than building visibility information in a separate map or matrix the horizon and shadows may be built into the primary data by setting pointers from one to the other.

Providing both vector geometry and raster cell topology at nested levels of complexity (Puppo 1996; Boots 1999; Mostafavi, Gold et al. 2003), the obvious data structure to represent visual-fields is the Triangular Irregular Network (TIN). The resolution variant properties of TIN are already used in most computer graphics applications where variable scale is important (Neves and Camara 1999). Even where DEMs are modelled as raster grids, they are usually transformed to TINs for projection on the computer screen - breaking the one-to-one link between landscape and screen objects (Neves and Camara 1999) and providing an additional source of error (Sang, Ode et al. 2005).

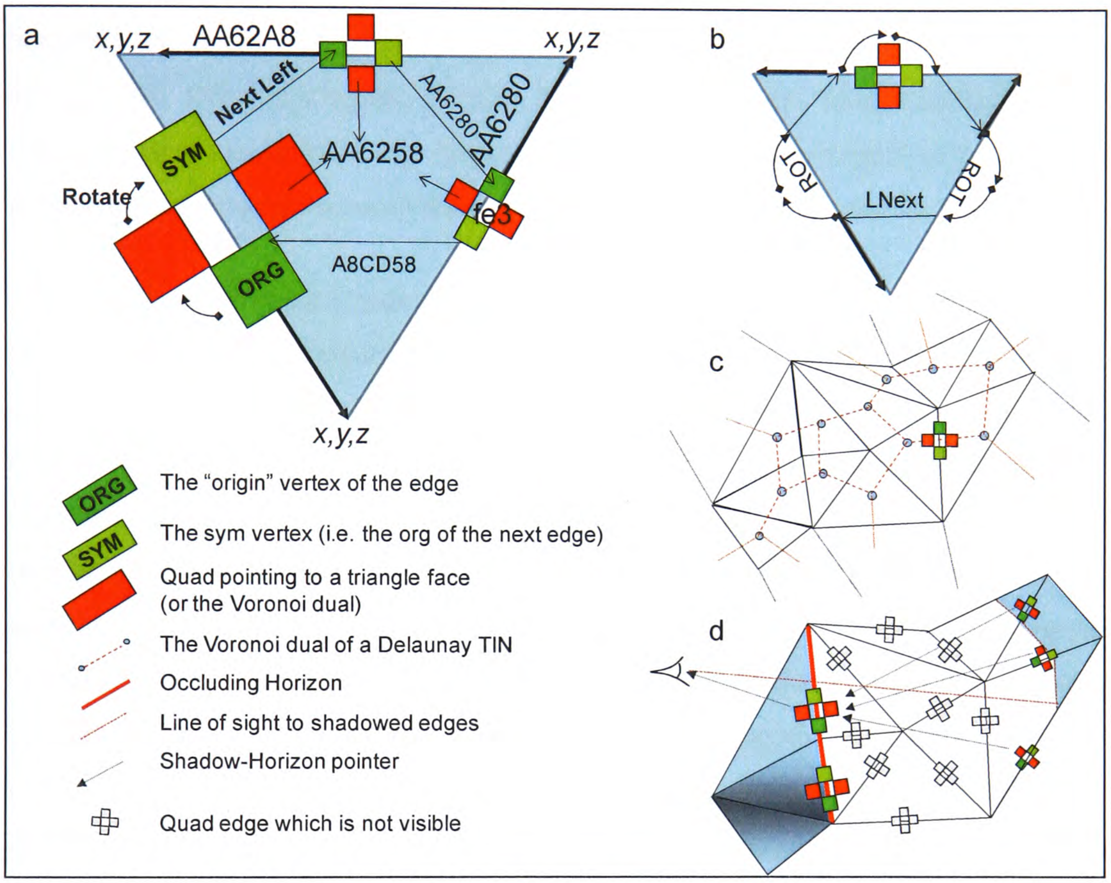


Figure 17 : (a) Constructing Quad-Edge Delaunay TIN, (b) navigating the mesh, (c) the Voronoi dual, and (d) embedding line of sight pointers

Quad-Edge TIN are a specific type of data structure which sets pointers between memory locations. For example the 'Org' memory space 'AA62A8' of the upper most edge in Figure 17a, holds the coordinates of the upper left vertex of the triangle. The location of the other vertex for this edge is the same point as the 'Org' for the next edge to the left (anti-clock wise on this page), so rather than both edges hold the co-ordinates, each 'Org' also has a pointer to its 'Sym'. The 'Sym' points to this second 'Org' - 'AA6280', which holds the co-ordinates for the upper-right vertex. Doing so establishes both the co-ordinates of the vertices of the edge and the fact that the two edges meet at the latter vertex. Figure 17b shows that by going from one edge's 'Sym' to the next edge's 'Org' (the LNext arrow), and 'rotating' around the four 'quad' squares that make up each edge to go from 'Org' to 'Sym' (the 'Rot' arrows) one can circumnavigate the whole triangle and so establish which edges join up where. The Quad-edge also holds pointers to the common memory space of the three edges ('AA6258') which can thus hold information about the triangle face they form the boundary of. If the triangulation is Delaunay (Delaunay 1934) then these pointers describe the Voronoi diagram (Figure 17c). Finally, higher level combinations of these functions can be built, e.g. 'Org.sym' so one can circumnavigate in the opposite direction and navigate the mesh from edge to edge or triangle to triangle.

Although the quad-edge structure could be viewed as a 'gold plated' version of TIN (which are generally memory intensive compared to fast compression methods (e.g. quad- and oct-trees)), the comprehensive description of the topological connections, and the simple and efficient navigation that provides, is arguably more important (see (Ledoux 2006 pp.17-20) for a detailed discussion). In particular, for Delaunay TIN the Quad-Edge structure can also explicitly incorporate the Voronoi area of each TIN node as its dual (Guibas and Stolfi 1985; Aurenhammer 1991). The Voronoi diagram is useful as it is a fundamental form of natural neighbour spatial interpolation (Gold and Zhou 1990), and the frequent result of many anthropogenic and natural processes (Aurenhammer 1991). As such both methods of interpolating data over a DEM (via discrete height units, or a surface of slopes) may be managed simultaneously[22]. The Delaunay-Voronoi dual structure also provides the necessary criterion for various useful spatial operations via a simple set of operators (Gold 2000; Mioc, Anton et al. 2007) in particular identifying attribute data by triangle face and guaranteeing a circular, nearest edge first scan away from a point (Gold, Nantel et al. 1996)[23].

---

[22]Standard TIN interpolate to planar slopes, however additional geometries such as splines may be added to provide more smooth interpolations Hugentobler, M. and B. Schneider (2005). "Break lines in Coons surfaces over triangles for the use in terrain modelling, *Computers and Geosciences*, 31, 1, pp 45-54."., these however generally limit the visibility analysis methods to ray tracing.

[23] By contrast, "single edge" mesh, represents the minimum data required to store the TIN, but is of limited utility, since the mesh can only be traversed as a space filling curve Bartholdi, J. and P. Goldsman (2004). "Multi-resolution indexing of triangulated irregular networks, *IEEE Transactions on Visualization and Computer Graphics*, 10, 4, pp. 484 – 495.". there is no guarantee of a traversal which will visit every edge once and only once.

3.6 Building Horizon-Shadow chains

Figure 17d shows the model of visibility that is the eventual aim of this section. In addition to the existing pointers that connect spatially adjacent TIN edges, pointers are added to connect TIN edges that appear adjacent from a particular viewpoint. It should be noted these pointers (dashed arrows) run from the shadowed edge to its occluding horizon, but need not follow the line of sight (dashed red line) as the link is only topological.

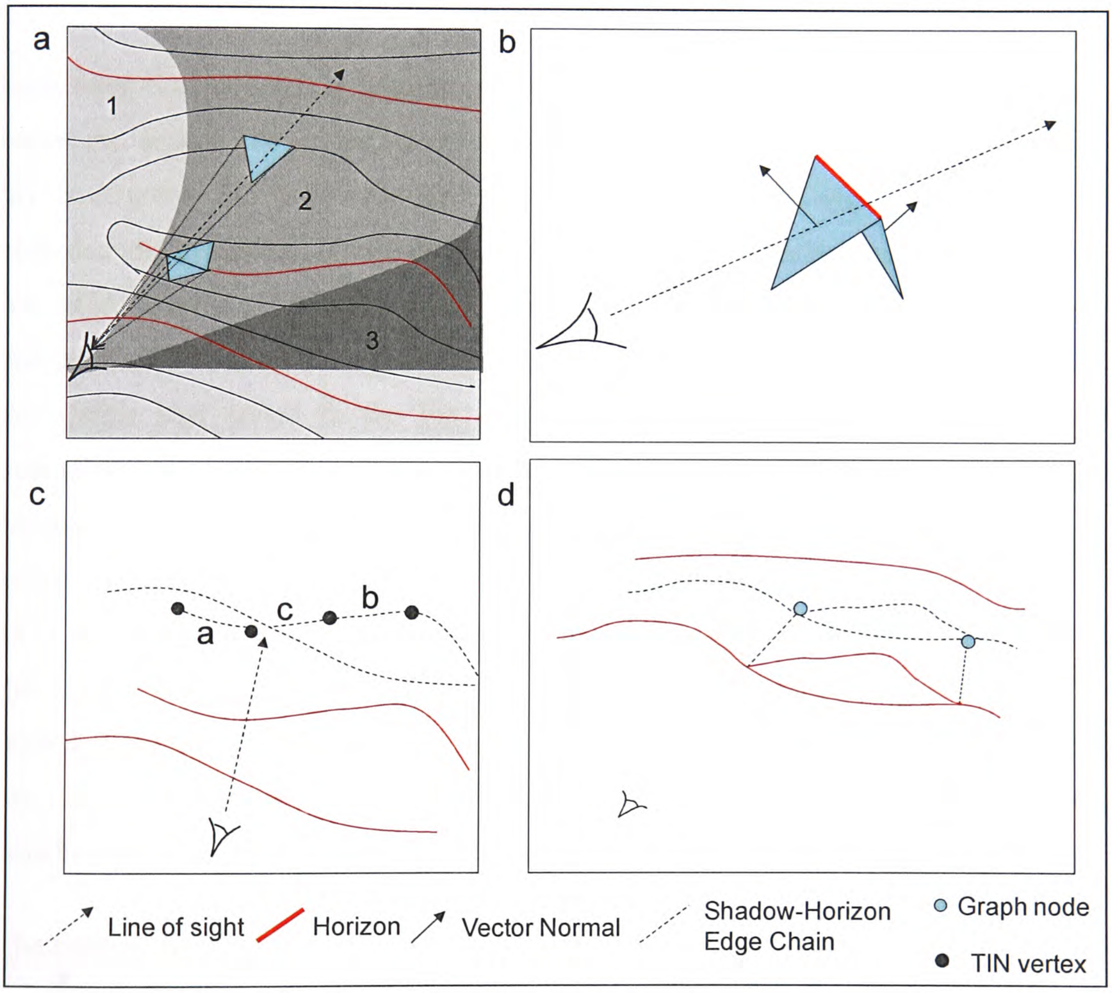


Figure 18 : (a) Scanning a mesh in three spirals, after Gold et al. (1996): (b) horizon determination, (c) visual intersection points and (d) the horizon graph.

Figure 18 illustrates the four stages in computing the pointers in Figure 17d. To identify the potentially relevant horizons the mesh is scanned in three spirals, as per the algorithm described in Gold, Nantel and Yang (1996). The three-tone areas in

Figure 18a (1,2,3) show the area to be scanned in numerical order away from the viewpoint. Thus the edge between the two neighbouring triangles in Figure 18(a) would be dealt with before the more distant triangle. Each edge forms the boundary between two neighbouring triangles. The nearer triangle is tested for back face culling (Zhang and Off 1997) via vector normal comparison (Figure 18b). If not visible it is ignored and the scan progresses. If visible, the neighbour is tested for backface culling. If this is not visible then a horizon must exist between the two, the common Quad-Edge is marked as a *potentially visible* horizon but Hidden Surface Removal must first be performed to determine if the edge is visible.

Each edge is considered as a point pair. It is assumed that there are no 'holes' in the landscape. Figure 18c shows three possible cases for the projected lines *a,b,c*. If case (*a*), both points fall below the topmost previously processed edge, it is considered occluded and discarded. If case (*b*), both are above the top shadow and it is a horizon, it is added to a list of visible horizons along with its projected co-ordinates. If case (*c*), one point of a horizon lies either side, the intersect is calculated and the geometry of the visible part added to the list of horizons. The resulting 't-junction' of the occluding and occluded horizon (Tarr and Kriegman 2001) forms a node in the horizon graph so the edge is also added to a list of 'shadow' edges, which includes a pointer to its occluding horizon and it is marked as being a horizon itself (Figure 18d)[24]. If an element is shadowed in by an occluding edge but is not itself a horizon, this is still recorded in the 'shadow edge' list but is not recorded as a horizon. Only occluded horizons therefore add a node to the horizon graph. Figure 18d shows the resulting graph, consisting of horizon edges, their shadow edges and linking pointers between the two.

The current maximal horizon can be maintained (as per Reif and Sen (1988)), so any point projected below this will not be visible. This HSR method also allows the horizon chain to be built:

---

[24]Reif and Sen (1988) propose a similar idea, but rely on pre-processing of a BSP.

Set up a memory space (HList) to hold the memory address of each visible horizon edge identified and its x,y co-ordinates on the view plane.

```
For each edge with starting node H1 and ending node H2;
    For a segment S with starting node S1 and ending node S2;
          Project S1 and S2;
          If there is an element in HList where S1x Or S2x > H1x and < H2x
                    Check other vertex against H1x and H2x
                    If Line entirely below HList THEN End
                      ELSE
                              If Line above HList THEN
                                   If horizon add to HList, Sort HList;
                              End
                              If Line must intersect HList Then
                                   Add pointer to Quad;
                                   If horizon add to HList and Sort HList;
                                   If storing geometry calculate linear reference;
                              End
                    End
          End;
    Next
Next
```

This method was implemented in VoronoiMagic, a Delphi based proprietary software package for handling Quad-Edge Delaunay TIN and using randomised height fields as test subjects. For a field of 100 points (roughly 500 triangles), with a height standard deviation of 18% using a standard laptop PC (Pentium 2Ghz dual core processor), scanning the mesh and identifying horizons and their shadows took 2 seconds. Processing the data for a scene, such as that in Figure 19, with 250,000 points (77,000 of which were >0 heights[25], height stdev 10%) took 28 minutes.

[25]The algorithm skips 0m edges as these cannot form horizons but they still constitute a small traversal time cost.

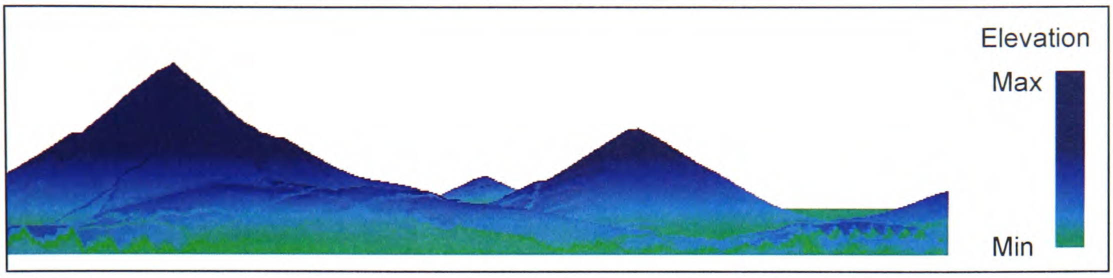


Figure 19 : A visualisation of the large test dataset.

This suggests the method is feasible for use in a planning context, providing statistics about a view from a chosen location for example. For dynamic situations however the feasibility will depend upon the application, in particular whether the dynamic element is attribute change, landform change, viewpoint change or all three and how these horizon-shadow links are stored once found.

3.7 Storing Shadow-Horizon links

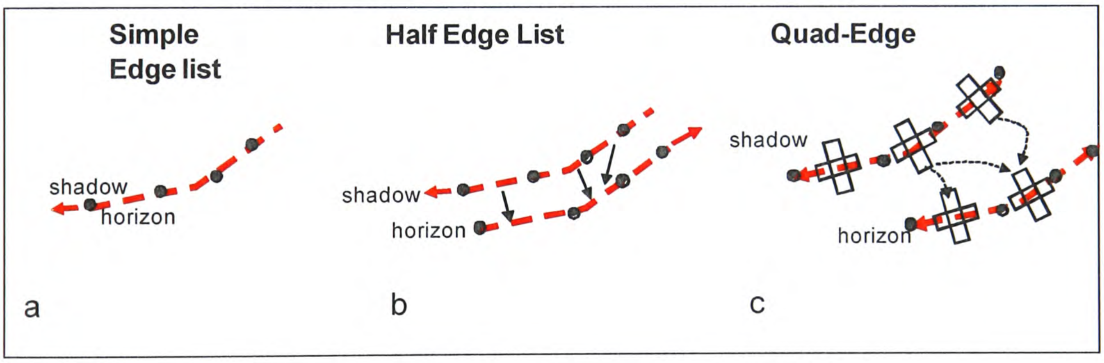


Figure 20 : Embedding Shadow-Horizon links into alternative TIN data-structures (a) Simple Edge, (b) Half Edge, (d) Quad Edge.

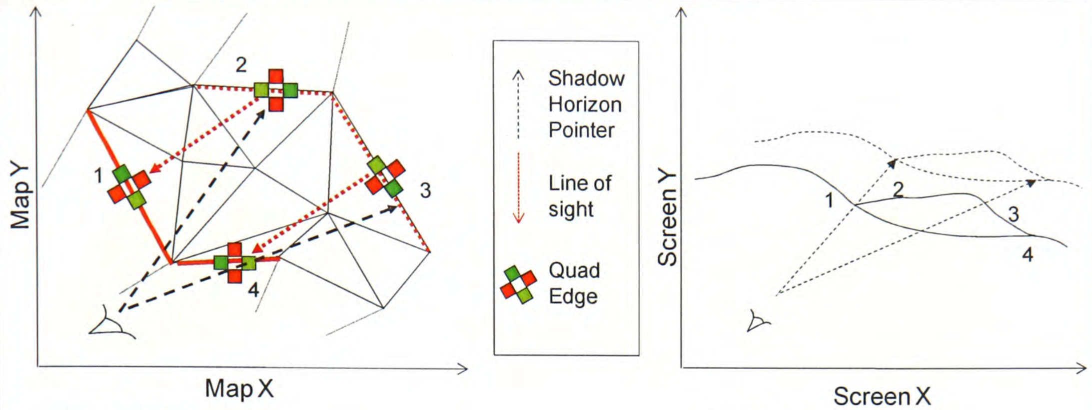
Pragmatically, the existing software base in Voronoi Magic provided a means of elegantly managing the quad-edge data structure. That the horizon-shadow chains would also be held using the quad-edge data structure did not necessarily follow. One option (Figure20a) would have been a simple vector structure, calculating the intersect points for over lapping horizons and building a separate list. This could have been achieved by image analysis of the output graphics or from simple element based visibility analysis (Madern, Fort et al. 2007). However it would not provide any link to the original data. The entire process would need to be repeated for any minor change in view point or landform. Other than a geometrically richer visual impact analysis (Madern, Fort et al. 2007) little is gained over existing methods.

The next step in terms of conceptual complexity would be to maintain a separate list of Quad elements forming the shadow and their respective horizon. This has the initially appealing advantage that the horizons may be accessed separate to the DTM and are self-contained so can be stored together as a list (Figure 20b). However, there is a an overhead in memory because Quad Edges involved in more than one viewshed would have to be referenced repeatedly; and in time because the mesh would need to be scanned to locate where in the DTM each element in the list was in order to establish how a change in view point or terrain might affect it.

The approach used (Figure 20c) was to embed the horizon-shadow pointers into the Quad-Edge TIN. An Occluding-Horizon attribute is added to each Quad-Edge, as and when a horizon-intersect is found a pointer is set from this, as the shadowed edge, to the horizon's edge forming a line of sight from background to viewpoint. The entire visibility graph can thus be approximately encoded for one bit of memory per shadow-horizon intersection and one bit per horizon or shadow edge.

The solution is scalable between storage capacity and accuracy, thus more accurate geometry can be encoded by providing linear references (Scarponcini 2000) as to where on the respective edges the intersection falls. For the small overhead of an additional list of pointers between the view point and the most distant horizon edges, or bi-directional pointers between horizons, the graph can be completely closed. This may then be queried toward or away from view points, and between viewpoints with mutual horizon edges.

Although not implemented here the method, by using lists of pointers per edge, could provide an efficient means to simultaneously store multiple viewsheds and navigate between them. Since the VM-LITE prototype is only concerned with single viewpoints, a list is maintained to reference the shadow edges in the mesh (which in turn reference their respective horizons) and their projected/occluded perspective co-ordinates, to avoid the need for reprocessing this during analyses (Figure 21).



Mesh attributes

ID	Quad Edge Memory Address	Partially Occluded by
1	A8DEC8	NA
2	A8DED1	A8DEC8
3	A8BEF7	B8CEA8
4	B8CEA8	NA

Perspective Coordinate list

ID	Start XY	End XY
1	4,7	5,6
2	6,6	8,6
3	8,6	9.5
4	7,6	10,5

Figure 21 : Embedding Shadow-Horizon links into Quad Edge TIN.

3.8 Applications

3.8.1 Attribute topology, landscape analysis and data accuracy

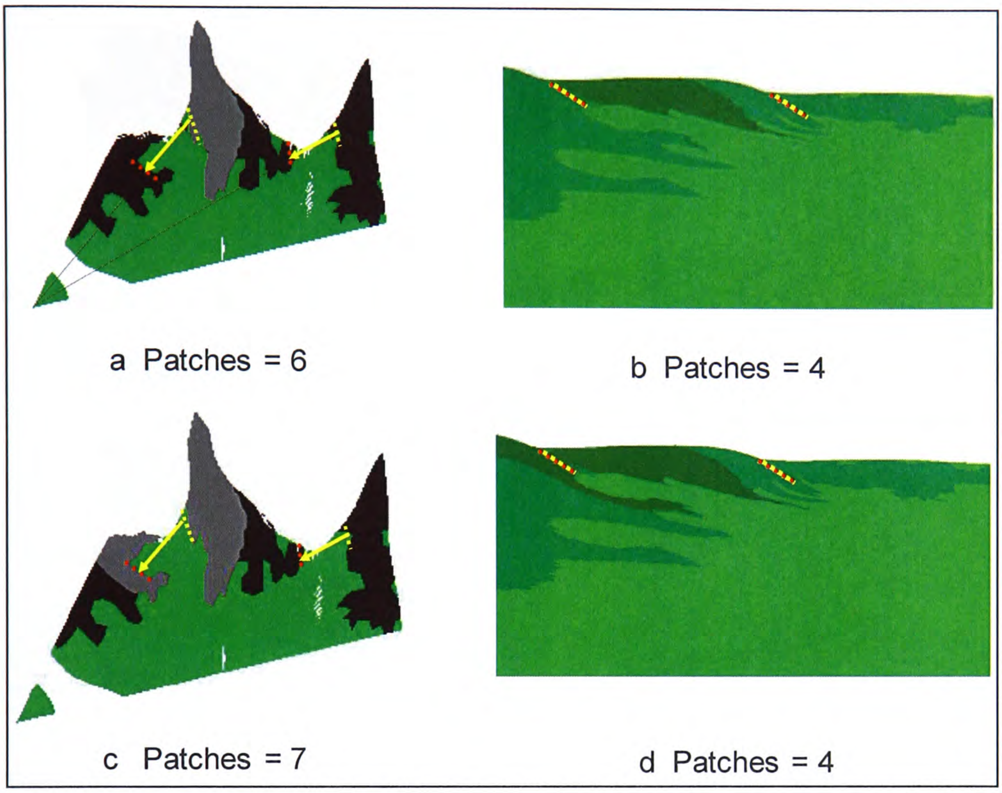


Figure 22 : Landscape change as measured by patch count in viewshed (a, c) and scene (b, d).

The effect of perspective on visual characteristics can be established directly through querying the topological shadow-horizon links (yellow arrows in Figure 22). Figure 22 illustrates how patch size (Tveit, Ode et al. 2006) metrics in the view may not follow changes in spatial complexity as is often assumed (Sang, Ode et al. 2008). The true visual complexity can be calculated by using the shadow-horizon links to navigate between patches on the map that are adjacent in the view, summing their area if also visually indistinct from one another.

If unit heterogeneity means that attributes will vary within a polygon on the DTM, but only part of that area is also intersected by the visual field, the classification may be incorrect for the visible area. As the shadow-horizon link provides pointers directly to the DTM, it is possible to detect when units are only partially visible and that issues of MAUP (Openshaw 1984.) may need to be considered.

3.8.2 *Landform analysis and change*

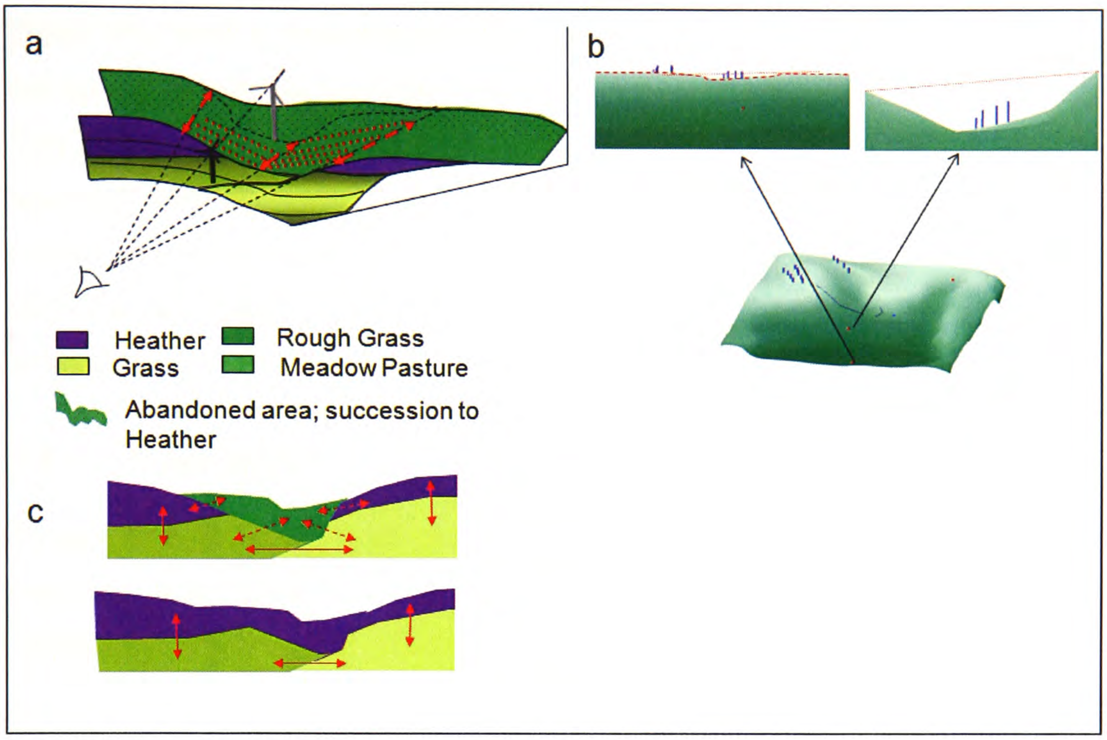


Figure 23 : (a) Establishing scene properties via Shadow-Horizon pointers; (b) scene framing effects and (c) scene patch complexity

The introduction of a structure to the landscape (e.g. a windfarm) may alter the content of the view (Figure 23a). This would be locatable with respect to the visual field between a horizon and its shadow. If the wind turbine is below the field (e.g. the lateral dotted red lines in Figure 23a) the change is not visible. Using pointers avoids the memory and maintenance overhead for storing the visual field as a geometric object. One need only check whether the line of sight remains valid and construct the plane when needed.

If a wind turbine is visible, the visual field can be used to limit the area of the viewshed that needs to be re-calculated to the area between the relevant pointer links. Furthermore, the graph of the horizons provides a context to such changes, meaning visual impact analysis could be made more sensitive to local effects on individual viewpoints. For example, the proportion of a 'framed view' altered by the development could be calculated by adding the convex hull to the horizon graph (Figure 23b).

Non-geometric attribute changes are also easily established from the pointer structure. Figure 23c shows the impact in perspective if the rough grassland (the dotted area in Figure 23a) were to be abandoned and eventually succeeded to heather. The dashed red lines in Figure 23a and Figure 23c are the same topological links. The solid red lines in 23c are the spatially adjacent topology that would be measured by standard landscape metrics such as contagion. Without the horizon-shadow links, the topology in the two images would need to be calculated through two separate analyses. With the links, the impact of a change in the map data on apparent patch size, contrast, richness etc. could be established almost instantly.

3.9 Conclusions

To assess the proposed method, one may consider whether it holds the potential to meet the three technical requirements and seven EIA relevant functions (a..g) identified.

Technical requirements:

i) The chain of horizons apparent in perspective view has been computed.
ii) The cross-horizon topology of the view has been computed and efficiently stored.
iii) The method provides for quickly detecting and analysing changes in the model, and for recording this information, including for multiple viewpoints if needed (view point change is dealt with in Section 4).

Functions :

a) *To support foremost: integration; visualisation; and dynamic update.*
The memory overhead seems likely to be acceptable for the added elegance of representation. The link between spatial analysis and visualisations is much stronger and dynamic update of the view due to changes in the geometry of attributes of the model is efficient.

b) *To be available by individual view (and incorporate) masked areas of the scene.*
Embedding the visual topology into the TIN provides the functionality of analysing characteristics in cross-horizon contrast or geometric arrangement that are highly specific to the view point.

c) *To provide summary metrics of landscape change.*
The horizons and shadows contain the topology of the horizon graph, and potentially its geometry also. In addition to visible and non-visible areas as available in standard, raster visibility maps, there is the potential to analyse visual complexity of horizons and effects such as visual framing (Bell 1998b), to give a richer visual impact assessment.

d) *Metrics need to be dynamically calculable along individual path choices.*
The line of sight pointers provide geometry by which to detect any change in the landscape and to test if it would be visible from previously processed viewpoints.

e) *Metrics to determine how representative viewpoints are.*
Sections 2 and 5 make the argument for the cognitive significance of horizon boundaries in themselves and their role as regulators of the variance in other landscape metrics, the method proposed allows their identification and navigation.

f) *Metrics to provide information on the robustness of data for representing the view.*
Since the shadow boundaries are mapped onto the 2D plane, it is possible to see where they fall in respect of other datasets such as land cover and so identify potential MAUP.

g) *Possibility to optimise between visually robust units and other demands.*
Provided scene metrics can be automatically measured, the raw material is available to allow visual factors to be included in SDI spatial unit design.

In theory at least, the method proposed has the potential to fulfill the requirements set out for an EIA SDI. In addition it may be able to provide computationally more efficient viewshed storage and provide a sufficiently comprehensive analytical capability for GIS analysis of perspective scenes to merit the term 'view analysis'.

4 Section 4 - Technical implementation

4.1 Introduction

Section 3 sets out three key technical requirements the software should meet and makes the case for the use of Quad-Edge TIN (QET) as a data structure to achieve these requirements. Section 4 follows the same structure, but focuses on the precise implementation of the methods advocated in Section 3. Rather than interrupt the text with large sections of code, this is referenced in the software through '# numbers' which may be searched for therein and in Appendix 1 (pseudo code) and Appendix 2 (code extracts). Some details of how QET are constructed and navigated are presented first as this functionality is key to understanding the subsequent implementation. This discussion assumes an understanding of basic Object Oriented programming principles and its syntax in Borland Delphi™ (see e.g. Cantu (2005) for further details). However for convenience it is worth elaborating on two key constructs:

Object Instantiation and Inheritance: An object, e.g. *ORoom,* is simply a Class (a piece of code) that can hold both variables (attributes e.g. XY-Location, colour) and methods (procedures or functions that do something with a set of parameters). They can *inherit* methods from other objects so the code need only be written once but can be used in many different contexts. For example, a house can have many rooms under one roof, thus the object *ORoom* can inherit the *Roof* property from the house object via *Ohouse.roof, i.e. ORoom* ***USES*** *OHouse.roof* along with common methods to every room such as 'switch lights on/off'. They can also be *instantiated* many times, i.e. the class *Room* presents a template of variables and methods, but many copies or *instances* of this may be made, each holding its own particular values within the variables thus *OHouse.room1.lights := On, OHouse.room2.lights := Off.*

Pointers: Pointers are a type of object that, rather than holding an attribute directly, points to another object wherein the variable or method of interest can be found. This might be useful, for example, if three edges end at the same node (i.e. they intersect) as all three can point to the same object. If the node-location attribute needs to be changed then only that common object needs attention, saving program time and eliminating the possibility that one edge might not have its node location changed, which would break the topology. It can also be used to link information together, in a list for example where each object has its own value and a pointer to the next object.

4.2 Quad-Edge Delaunay TIN construction and navigation

The basic building block of the QET is the *tQuad*. The tQuad is a proprietary class to VoronoiMagic which builds directly on tObject (tObject being the root class for all Delphi objects). The tQuad has methods called edge-operators, which set pointers to memory space holding attributes. One points to its 'Org' (an object holding the co-ordinates of its originating node) a second to its 'Sym' (another tQuad the 'Org' of which holds the co-ordinates of the node at the other end and whose Sym points back reciprocally). These two tQuads together form one double sided 'edge', (Figure 24, see also Figure 17a of Section 3). But the tQuad also has methods to set pointers to two more tQuads, which in the Delaunay model represent the Voronoi dual of the QET. Through sharing common nodes and through pointers to a common Voronoi node, three edges become connected together and each reference the common triangular space they enclose.

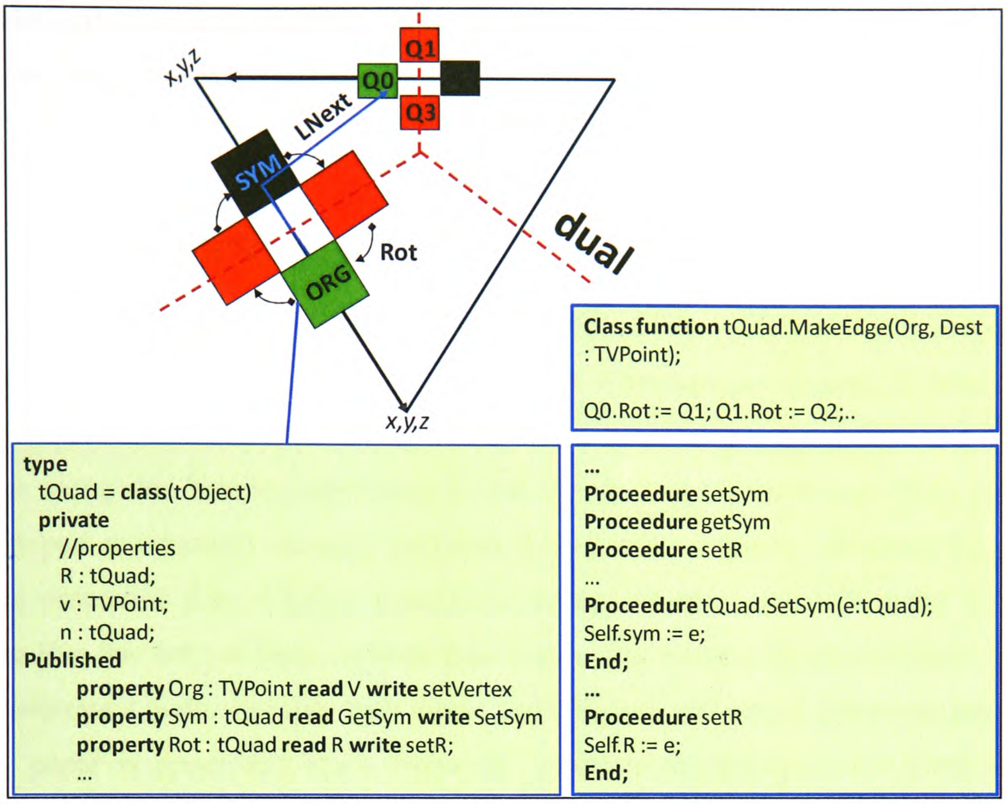


Figure 24 : Procedures for building quad-edge TIN

In order to build a mesh of these Quad-Edges which can be navigated quads also have properties which reference scripts to set and read additional links (Figure 24). In particular, the *Rot* property sets a pointer to the next quad in the quad edge, allowing rotation around the quad edge so that one can work with either the edge or its Sym (which points in the opposite direction), or with the Voronoi dual (which represents the triangle faces). LNext moves the current tQuad (usually 'e' or 'QCurrent' in the code) to the next triangle edge in an anti-clockwise direction. Combining the two commands one may move from triangle to triangle, edge to edge or node to node. Voronoi Magic is an expanded implementation of the processes develop by Guibas and Stolfi (1985) which sets out the fundamental operations.

One function that was not pre-coded was the option of attaching attributes to the Delaunay edge itself. They could be added to either side of the edge (in the Voronoi dual quads) or as attributes of the Sym and Org, but there was not a common attribute space that both sides of the Delaunay edge could reference. '*EAtt*' was included to provide this function (#32.02). This contains the '*FOccH*' field which holds the memory reference to the horizon edge which occludes a shadow edge.

4.3 Scanning the mesh

Hidden surface removal is simpler if one can be sure that once one edge is processed no other edge will be found that occludes it. This can be ensured if edges are processed in distance order. However, since the space is two dimensional, ordering edges along the distance dimension is not simple. Gold, Nantel and Yang (1996) developed an approach whereby the mesh is navigated in spirals. Provided the edge being processed does not face toward the viewpoint, the spiral will never enclose space that has not yet been scanned (see Figure 18a in the previous Section). They demonstrate it is theoretically both robust and efficient, and indeed for the purposes of their paper is practically ideal. However, visibility calculations are a particularly demanding application for computation. As will be a problem met several times in this Section, the resolution of the calculation can have a critical effect on the key decision on which the scan algorithm depends. For this reason, and because it was very difficult to test subsequent elements of the code if unsure whether an error might originate earlier at the scanning stage, a second scan was also implemented. Although it also suffers from problems with the resolution of the calculations required, this is in different circumstances. Therefore if the same error occurred using both scans one could be reasonably certain the fault lay at a later stage in the process. For practical purposes however, the 'Outside-In' approach is the more robust and efficient of the two.

4.4 The Outside-In approach

To understand why both scans were needed for testing, the key part of the implementation in VoronoiMagic is examined. The code was implemented by others and since it was never intended for, or tested against, this kind of application no criticism is implied of the implementation.

The primary scan algorithm is based on the Outside-In approach of Gold, Nantel and Yang (1996) and resides in a class named mesh.MeshVolume2. It is called three times (#22) one for each side of the starting triangle at which the viewpoint is located. A single repeat-until loop is used to continue the scan until the previous step returns no further edges to process.

The edges of the starting triangle are labelled, the nearest to the viewpoint being Edge one, then edge two and edge three in anti-clockwise order. Each edge is checked as to whether it is 'Up' or 'Down' ('Down' implying that crossing that edge leads to space further from the view point, 'Up' nearer the viewpoint). This distinction is made by putting the co-ordinates of its two nodes and those of the view point into a matrix and calculating the determinant thus :

Equation 8

(a) DIn2 := Det(In2.Org, In2.Sym.Org, ViewPoint).
(b) DIn3 := Det(In3.Org, In3.Sym.Org, ViewPoint).
(c) DD := Det(Edge1.Org, In2.Org, In3.Org)

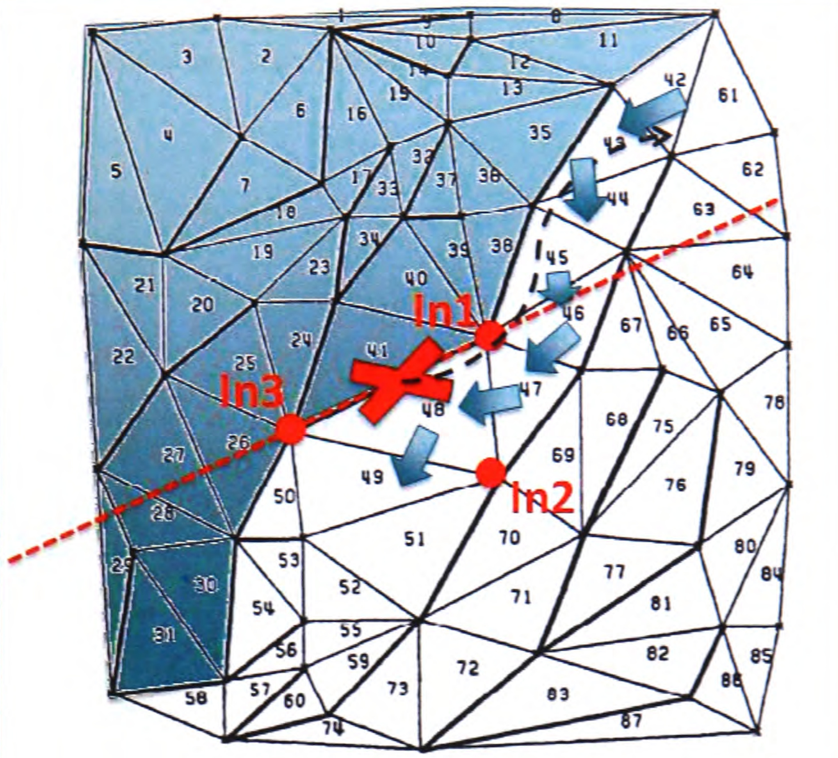


Figure 5. An ordered triangulation (from Gold and Maydell 1978).

Figure 25 : The Outside-In Triangulation Scan Approach

The determinant of the edge nodes and the view point will be negative if their geometric centre is within the triangle formed by the three points (Figure 25). If negative, the vector normal must be pointing toward the viewpoint (marked wth a red cross in Figure 25 because crossing that edge would lead into nearer space). Thus, by processing an edge only when the result of the determinant is positive, the scan will only ever move away from the viewpoint along the line of sight to that edge (i.e. from triangle 48 to 49 in Figure 25). However, as Figure 26 shows, the edge may lead away from the viewpoint, but the triangle may be shaped such that it encloses space which is closer to the viewpoint along another viewing vector. Thus it is necessary to consider the determinants of the other two edges also. Figure 26 shows the combinations of positive and negative results which may allow an edge to be added to the scanned area[26]. Should none of these options arise, the scan simply returns to the last option found yet to be processed, or ultimately to the next edge of the starting

[26]Reproduced from Gold, Nantel and Yang (1996) by kind permission.

triangle. A Delaunay triangulation ensures that a graph can always be found to complete the entire data set (Gold, Nantel et al. 1996).

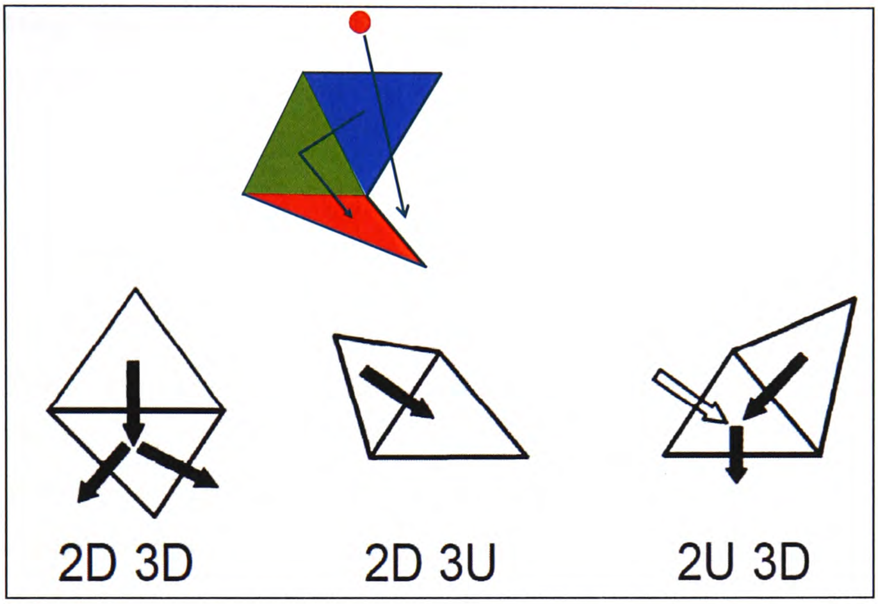


Figure 26 : Decision making process for Outside-In scan

A problem occurs when the geometry of an edge is closely aligned with the direction of view and very distant – producing sliver polygons in perspective. In this circumstance, a small rounding in the determinant calculation can result in an edge being classified as 'up rather than 'down'. This produced two types of problem 1) mis-ordering of edges when one spiral is terminated too early, 2) premature ending of the scan before the whole area is completed because an edge which should have been valid to progress the scan was classified as invalid. These cases are very rare and seem to occur only in specific circumstances; small, highly rectilinear datasets where the size of the elements is within a particular range relative to the distance to the viewpoint *and* where that view falls along a straight line running into the depth of view. Unfortunately, these are the very circumstances needed for the development of the Visual Topology software, because the elevation data need to be sufficiently simple to be interpreted manually in order to establish if later stages are operating correctly. This issue did not arise when running the scan on the more complex datasets used in final testing. Case (2) is catastrophic, but therefore also easily identified on the rare occasions it occurs. Case (1) was more problematic because one could not be sure if an error in the hidden surface removal or visual-topology result was due to that algorithm failing or the vertices being visited in the wrong order. Implementing more robust computation would simply reduce the rate of occurrences further not eliminate the issue.

4.5 An alternative scan

To improve testing of the HSR and visual topology methods, an alternative scan was implemented (*tMeshDelaunay.VNDScan*, #30). This scan works by following a single anti-clockwise spiral. As it progresses, previously visited edges are tagged so that the spiral cannot revisit them (#30.06). Each potential edge is checked to ensure it does not partially enclose unprocessed nearer space using the class *toolsGeometry.IsInsideTriangle* (#30.09). The aim is to establish whether or not the new node (that is the node of the test edge which is not also a node of the previously processed edge (i.e. the parent edge)) falls along a line of sight which intersects the parent edge (Figure 27), which would therefore also only cross previously processed space.

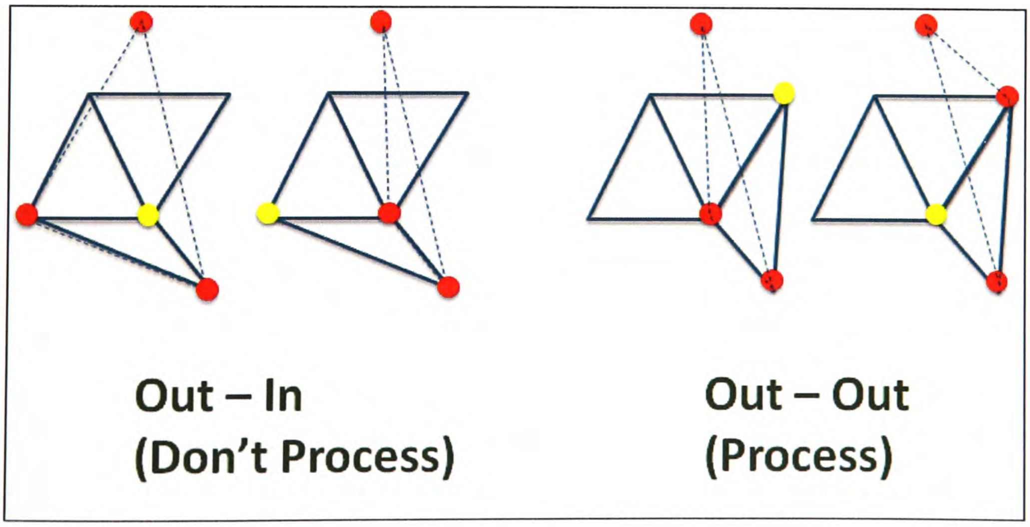


Figure 27 : Decision making process for alternative TIN scan

To do this the viewpoint, new node, and one of the parent edge's nodes form a triangle. If the other parent edge's node falls within this triangle, there cannot be such a line of sight and the edge must wait to be processed later. *toolsGeometry.IsInsideTriangle* puts these points, along with the test point, into a series of matrices, to test each edge of the triangle (similarly to the Outside-In approach). If all three are positive, the point is within the triangle. Rounding errors are more likely to produce a false negative, but are less likely to produce a false positive – because the point would need to be very close to all three edges of the triangle for a false positive but only one edge for a false negative. This makes mis-ordering errors less likely, but failure to find a valid next step in the path is more likely. So a second difference is that, if no edge remains to which the scan may move, it takes a random walk back through the processed area until the hull of the processed area is again reached and the scan resumes. The scan functions well for the development circumstances, which was important for testing subsequent steps on small data sets (that for practical reasons tended to be rectilinear), but it is far slower for large data sets with realistically complex surfaces, when the original rounding error has not, in any case, been noted.

This algorithm was therefore mainly used in the development stage, with the 'Outside-In' approach being that for application and a useful double check if there was some doubt as to the whether the origin of a problem might be scan related.

4.6 Edge processing

Once an edge has been determined as valid by either scan, it is sent to *TMeshDelaunay.EdgeProcessing* (#27.02). This consists of eight separate sub-processes :

1) Back-face Culling and Horizon Identification (#27.05 calling *TMeshDelaunay.TraverseScript* #28);
2) Co-ordinate system transformation (#27.08 calling *TMeshDelaunay.RotateView* #29);
3) Projection (#27.35 calling*TMeshDelaunay.PerspectiveTransform #31)*
4) Hidden Surface Removal
    a. Part 1 (Split Trapezoid) (#27.09)
    b. Part 2 (Point in Polygon) (#27.261)
5) Horizon-Shadow Link Setting (#27.291)
6) Intersect Geometry Calculation (#27.29)
7) Drawing Perspective View (#27.331)
8) Drawing Map View (#27.332)

4.7 Back face culling and horizon identification

Back Face Culling (BFC), and the concomitant horizon identification takes place in *TMeshDelauay.TraversScript* (#28.01). This could arguably take place after co-ordinate transformation in order to make the usual comparison of vector normals (Figure 18b, Section 3) simpler. However, it was realised that visibility or otherwise of the triangle face could be established simply by determining whether at the location of the view point in x and y, the plane of the triangle would be above or below the viewpoint (Figure 28). This is determined through simple trigonometry and vector addition to establish the z-value of the plane at the x,y location of the viewpoint. Vector normal is the more standard approach and may be advantageous for use with an index (e.g. binary space partition as discussed in Section 3). However this approach proved effective and its simplicity is felt to be advantageous given that small number issues again presented problems (#28.05 eliminates program errors due to very small vector components).

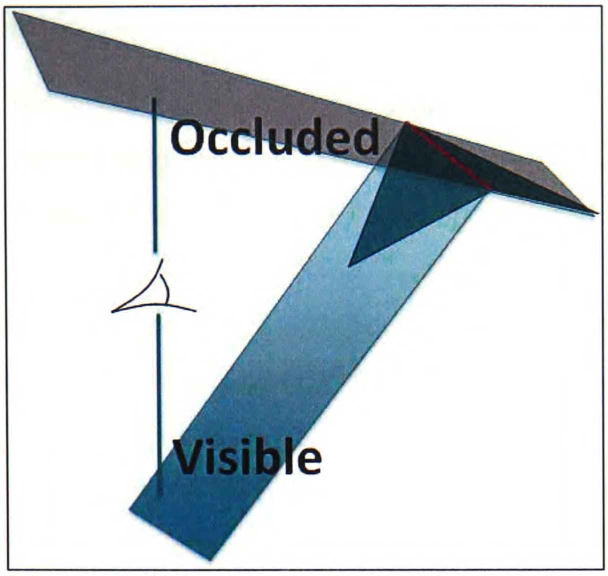


Figure 28 : Determining visibility of triangle faces

The process is repeated for both triangles either side of the test edge (#28.06). The results are then compared (#28.09) and if different then the result (*HCheck*) is returned as 1, else 0 is returned meaning no further stages (including co-ordinate transformation) need to be undertaken because the edge is not a horizon.

4.8 World co-ordinate to perspective coordinate transformations

The purpose of the co-ordinate transformation is to align the y axis of the data with the depth of view for projection. Each test-edge node, along with a pre-calculated viewing angle[27], is sent to *TMeshDelaunay.RotateView* (#29). The relevant 90° quadrant is established relative to the viewpoint and the angle *from* the view point calculated, which is then subtracted from the viewing angle (#29.02). This is then converted back into the XY co-ordinate position the point would have if the Y axis were the depth of view (#29.03) and returned to *EdgeProcessing* as a point (#29.04).

[27] For simplicity when running thousands of tests it is presently assumed that the viewing angle runs from the view point inward toward the centre of the data set. Other options would simply require affine translation of the origin to describe another vector.

4.9 Projection

The mathematics of the projection transform has already been presented in Section 3. However it is worth considering the code (*PrjViewCode.PerspectiveTransform,* #31) in order to explain certain limitations. Firstly the distance to the screen, which might be loosely considered the focal length (#31.01) is hard coded as is the angle of view (#31.02). Changing either of these might generate new or exacerbate known problems in later stages. For example a more distant screen would result in smaller images, so increasing the possibility of topological changes due to screen resolution. This problem arose during testing since the computer could identify loops in the horizons which the map showed to be correct, but which were not visible in the perspective rendering on screen. A wider view angle would result in 'fish eye' effects so a flat projection screen could not be readily assumed sufficient. The key transformation is given at #31.04, where by the x co-ordinate is transformed to the screen co-ordinate via the term *thetaX* which is the angle of the x co-ordinate to the depth of view as adjusted by *RotateView*. However, note that *RotateView* only transformed the co-ordinates in 2D, to align the Y axis with the depth of view. For views angled down, onto a landscape below the viewer, this would leave an affine shear uncorrected. The code is effective only for view heights near to zero. This is sufficient to develop and test the horizon analysis, which is the key scientific interest, and for the practical scenario of a person standing on a boat looking toward the shoreline or on a plane looking toward hills. But a more sophisticated solution to the co-ordinate transform would be needed in order to consider viewpoints where the depth of view cuts across the Z dimension.

4.10 Hidden Surface Removal 1 – 'Split Trapezoid'

Hidden Surface Removal (HSR) follows two methods, the first of which (#27.09) uses the *geometry.isinsidetriangle* class to determine if either of the vertices of the edge that is being tested for occlusion fall inside either of the two triangles which may be drawn between the potentially occluding edge's vertices, and the viewpoint (Figure 29)[28]. Once every potential occluding edge has been tested, three simple rules can be applied to remove hidden surfaces:

1) Neither vertex is within any triangle, entirely visible.
2) Only one vertex is within. Calculate intersection with horizon, move the projected co-ordinate of the hidden vertex to the intersect point.
3) Both vertices are within at least one of these triangles – (a) hidden unless (b) intersections establish middle of edge visible in which case move the projected co-ordinates to the intersect points.

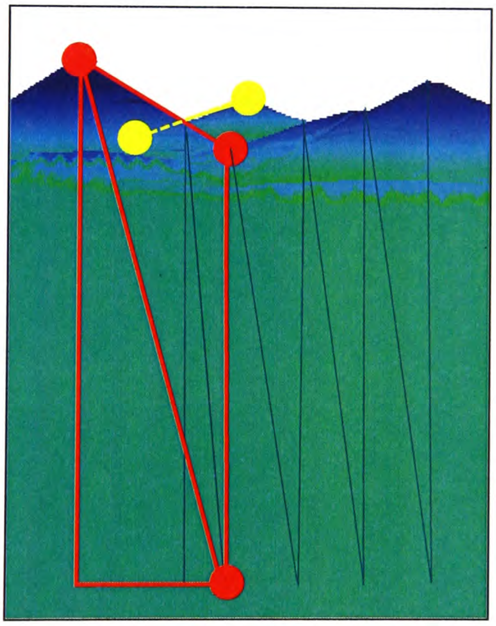


Figure 29 : Identifying visual horizon intersections by split trapezoid

[28] An initial glance at Figure 29 might suggest that these triangles should 'fan out' from the viewpoint. Spatially this would be the case, but it needs to be remembered that the x-axis in the perspective view is in fact part of the circumference of the angle of view.

Each horizon identified as visible is added to a list (*FormMain.Form1.PrjHorizons*) at the time they are drawn on the map (#27.34) along with their projected co-ordinates. This serves as the test list for each new edge. There is no absolute reference for the vertices of the test edge, so as each test is performed a variable *BelowPoint* is set to either -1 or -2, depending on whether the first or second vertex was found to be occluded (#27.24). As the other vertex may already have been established as occluded by a previous test, if this variable is not 0, then it is set to -3, to record the fact that both vertices are occluded. However, after each 'inside triangle' test, if BelowPoint is either -1 or -2, the test edge is tested for any intersection with any of the potentially occluding horizons so far considered (#27.27)[29]. Every potentially occluding edge must be tested for an intersection (using *geometry.twolinesintersect #27.27)* because the node may fall below one edge but the test edge rise above the current horizon behind a different, closer, occluding edge. If such an intersection is found then the projected co-ordinates of the hidden node (determined by BelowPoint) are set to those of the intersect point (established via *geometry.IntersectionPoint* #27.28), and as this point is visible, BelowPoint is set back to 0 (#27.29). Subsequent tests, against more distant horizons, will therefore only consider the visible portion of the test edge.

[29] Note here that a slight adjustment is made to the co-ordinates of the test node if either of the earlier horizon nodes is found to be identical in both test and horizon edge, as this produces a divide by zero error.

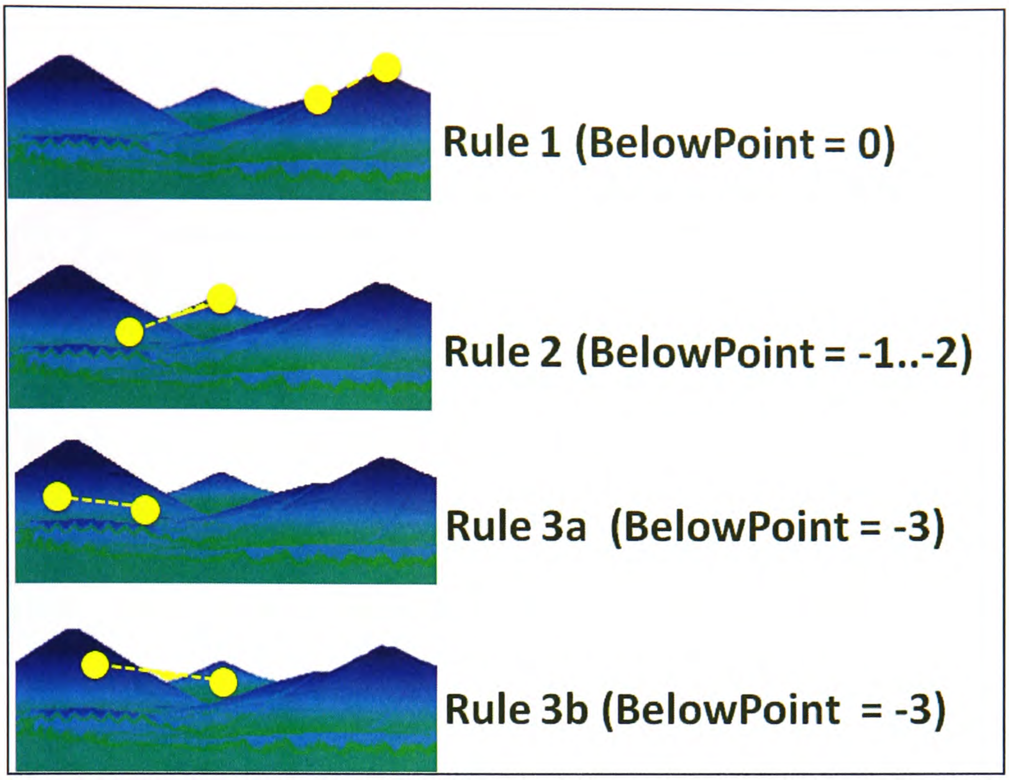


Figure 30 : Hidden Surface Removal and Visual Topology Determination

If one or other point is below the horizon the situation is clear. If both points are below the horizon, it is possible that the edge runs between a gap in the near horizon, as per Figure 30 Rule 3b. An early premise of the work was that distant horizons would be so much smaller than near horizons that this would never occur in practice, nor would it be possible for a near peak to intersect a single edge in the distance. For this reason each edge can only have one occluding horizon edge. Multiple occluding horizon edges would be possible by replacing the *FoccH* attribute with a list attribute, which could provide for maps with multiple view points, but this is unnecessarily complex and inefficient for the simpler single view point context. However, in order to be able to visually assess the correct functioning of the software, datasets were used with a few very large terrain features built from a small number of edges. In this context the situation in Figure 30 (rule 3b) can occur, thus the code provides for its handling visually (#27.3) but only sets the first of the resulting horizon-shadow links.

Once the test edge has been compared with all edges in *PrjHorizons* the rules are applied to establish the correct final geometry of the projected edge (#27.33) and determine whether this should be drawn.

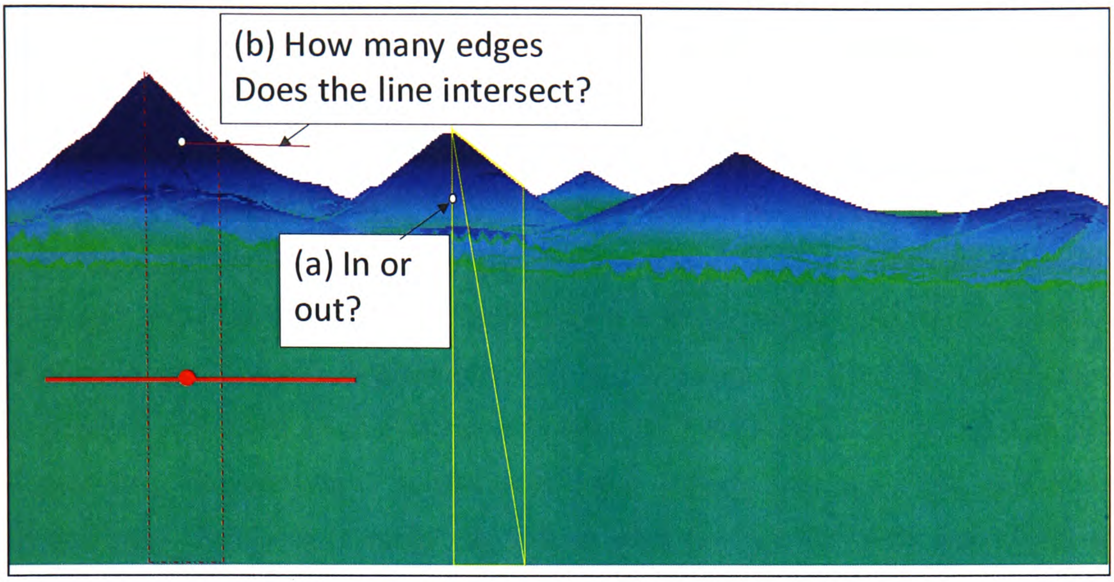


Figure 31 : Problems with Split Trapezoid and Point in Polygon HSR

This algorithm works in the vast majority of cases. However, as with the use of the determinant of a triangle to direct the scanning algorithms, small numbers can mean some cases give a false result. Figure 31 demonstrates such a case where point (a) falls so close to the edge of a triangle that rounding at the limit of the computational resolution tips it either in or out at random. This only rarely occurs, but the larger the dataset and smaller the horizons in perspective the more chances there are for such a situation to arise. If the result is that an edge is visible which should be hidden, it may also be added to *PrjHorizons* so subsequent test edges can intersect it and be determined as visible (because this sets *BelowPoint* to 0) when they are in fact occluded. Thus a small rounding error can grow to affect significant numbers of edges.

4.11 Hidden Surface Removal 2 – 'Point in Polygon'

It was decided to replace the split-trapezoid method with one which does not rely on the determinant of a matrix. Instead of representing the space below a horizon edge using two triangles, it is considered as a simple polygon (dashed red lines in Figure

31). The standard line-intersect approach used for 'Point in Polygon' operations in GIS (Laurini and Thompson 1999 p.267) was employed (#27.261).

This was originally implemented as a replacement to the first strategy. However, here too the very small geometric distinctions needed to calculate geometry in perspective caused problems. For example, consider point (b) in Figure 31. The line to the right runs very close to the corner of the polygon, so when each edge is intersected in turn, does this count as one or more intersections? Haines (1994) notes this ray-vertex intersection problem in a detailed analysis of the accuracy limitations of various point in polygon operations as do (Huang and Shih 1997) and (Schirra 2008). So it would appear that the problem is fundamental when dealing with very fine geometric distinctions. More robust recent algorithms exist but require additional checking operations and preprocessing which bring their own accuracy problems (Yang, Yong et al. 2010). As a pragmatic solution, the point-in-polygon approach was used to check the results of the split-trapezoid approach.

4.12 Setting the Shadow-Horizon links

When an intersection is identified the occluded edge has a pointer attribute, tQuad.FOccH, set to the memory address of the occluding tQuad, so although the term Horizon-Shadow link is more intuitively related to the sequence of view, Shadow-Horizon link (SHLink) would be more accurate. A line is drawn on the map (Figure 32) between the mid-points of each edge, not the points at which the intersection occurs, and so does not always fall along a line of sight spatially. This is intended to emphasise that the links are topological not geometric. Unless there is a topological event, the map will not change under viewpoint change.

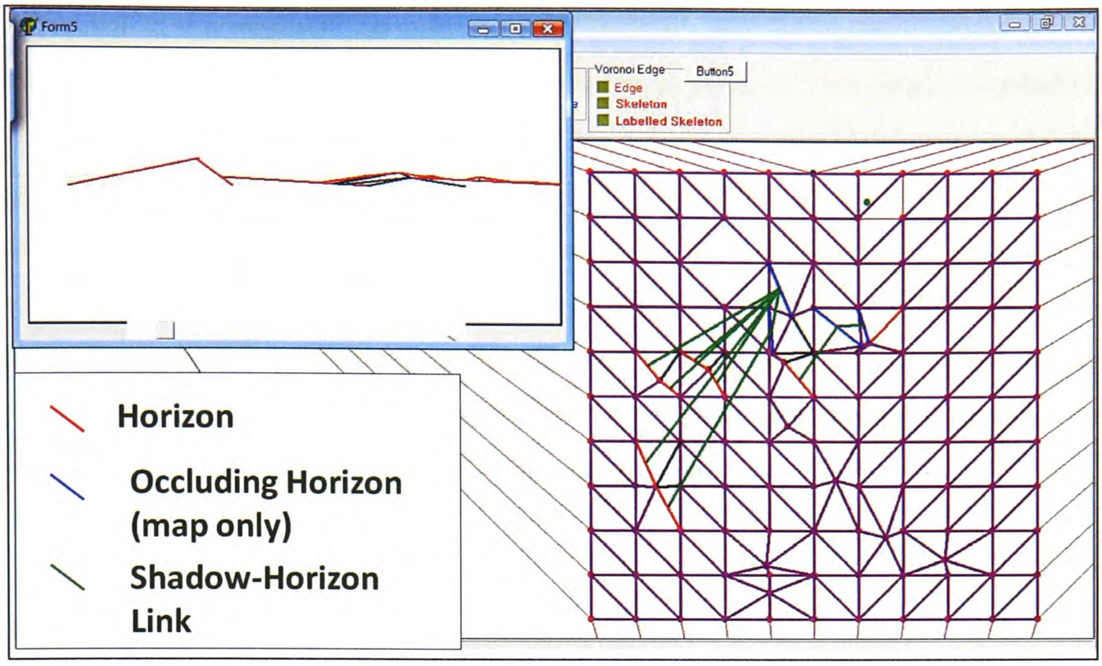


Figure 32 : Perspective and map views of a horizon graph and Shadow-Horizon links

A list of the shadow edges found to be part of the view is maintained in Formmain.Form1.PrjShadows, including at this stage whether it is a horizon itself and the co-ordinate positions of the edge's vertices in perspective. This is in order to avoid having to rescan the mesh for this particular application. The pointers and horizon attributes are themselves sufficient to store the entire viewshed for that viewpoint. Even in very large datasets, very few edges would need to be put back through the HSR to recreate the view itself, the number being more a function of the horizon complexity than the number of elements in the terrain. Even the geometry of apparent intersections could, if preferred, be stored within the mesh by recording how far along each edge, e.g. anti-clockwise, the occlusion occurred.

4.13 Graph traversal and Euler calculation

The resulting list, PrjShadows, is not in graph form, that is one cannot simply assume that edges adjacent in the list are either spatially or visually adjacent, nor that in any one view there will be only one horizon graph, near and far horizons may have no connecting edges. To avoid confusion the graph of horizons, shadows and SHLinks embedded in the map will be referred to as mGraph and the apparent graph of the horizons which is actually seen will be referred to as hGraph. Two stages are needed, firstly the edges need to be placed in an order such that visual adjacency can be assumed (4.14 building the mGraph). Secondly the components of the horizon graph need to be identified (the end nodes, visual link nodes and horizon-graph edges, hereafter referred to as hENode, hLNode and hEdge respectively to distinguish them from the mesh nodes, mesh edges and SHLinks). Both processes take place in the class TForm1.Euler (#40). In hindsight these two stages could (perhaps) be achieved simultaneously, but this was not clear beforehand.

4.14 Building the Map Graph (mGraph)

In order to manage the edges with the aim of only processing each edge once, the list PrjShadows is transferred to a stack nList (#40.33) where they can be 'popped' from the top in order, and are not replaced. The edges are added to the stack in reverse order to the list so subsequent processing will take the most distant edges first because the mGraph (e.g. Figure 33b) is a directed graph, in which one can only locate occluding edges from occluded edges, not vice versa. The basic method for connecting mesh edges into graphs was to take a starting edge tempQuad from nList and rotate around the node at either end, comparing those found to the list of edges in PrjHorizons. If a match is found this is removed from nList and pushed into a second stack testList (#40.12). Edges in testList will be spatially adjacent to tempQuad and can then be compared with edges already added to the mGraph (a list called HGCurrent (#40.091)) to see if the tempQuad has any neighbours in common. Beyond matching immediate neighbours to the current mGraph however, there are two general options to progress the scan.

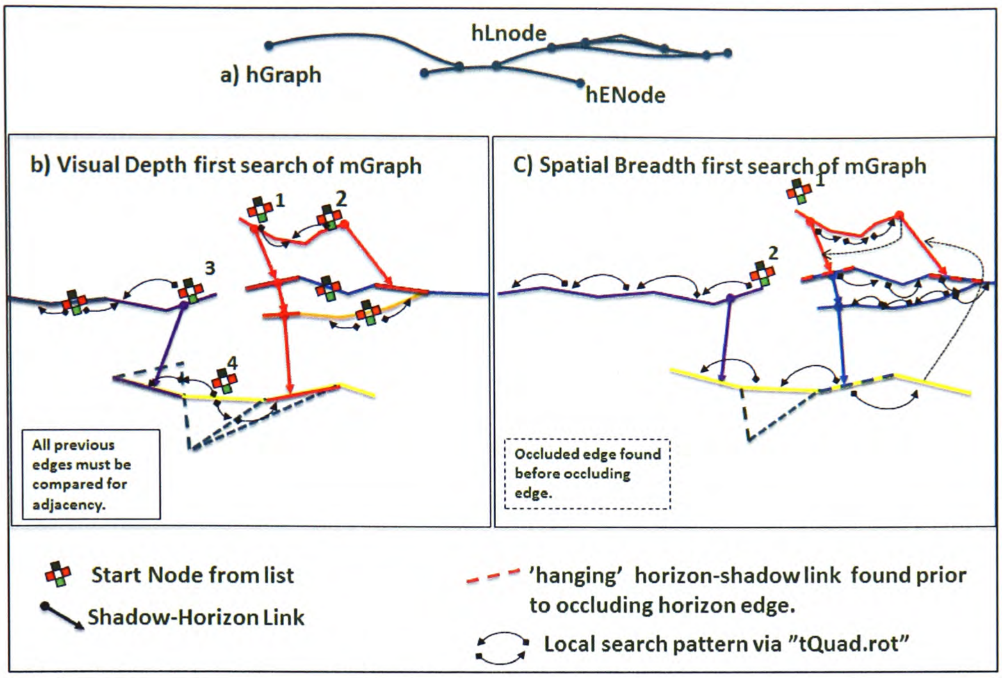


Figure 33 : Two alternative ways of scanning the horizon graph(s)

Reading the map-graph from root to branch is simplest, however the graph also starts from multiple roots, and the input list is spatially correlated in two dimensions so nList is only approximately sorted by distance. One could follow a depth-first approach (Skiena 1998 p.91) and so follow each occluded edge's SHLink toward the viewpoint before travelling further along the branch or taking a new starting edge from nList (Figure 33b). The advantage of this approach is that if an SHLink is found, the relevant occluding edge is added before moving on, so one does not have 'hanging' SHLink nodes in the graph waiting to be connected. However edges may also connect into loops due to sharing a common mesh node. This will not be discovered until later when each branch is traversed. Since one cannot assume that edges distant in the list are not in fact spatially adjacent, one would have to compare the 'n' neighbours of each new edge found with every edge already added to the graph.

A breadth first approach (Skiena 1998 p.89) faces the opposite problem (Figure 33c). Here, each spatially connected sub mGraph is traversed completely, before following the SHLinks to other sub mGraphs. Rather than having to compare new mesh edges to those already in the mGraph, one already knows it to be connected to the previous edge. The problem however is in joining the mGraph parts together via the SHLinks.

These links are stored as an attribute of the occluded tQuad. At the time that tQuad is processed, the corresponding horizon edge may be yet to be found, so will not exist in the overall mGraph. When that horizon edge is found, there is no information as to which edges, if any, it shadows. To find the HSLink, one would need to go back through all the processed edges and compare the horizon with their FOccH attributes. Most of the time, this would be a fruitless search as proportionately few horizon edges occlude other horizon edges.

The process is further complicated by the fact that, if no common edges are found between the HGCurrent and previously processed mGraphs, a list of mGraphs must be maintained which may or may not eventually merge. This is maintained as a list (HGA) of records (HGCurrentRec) which contains fields for both the list of edges constituting the mGraph and fields for attributes relating to that list, e.g. number of edges and nodes (#40.041). Each record in the HGA is searched for common edges to those popped from the testList. If none are found, the edge is added to a new HGCurrent. If a match is found, all the edges from the matched record (HGOld) are added to the HGCurrent and deleted from HGA (#40.239). The number of times this operation occurs is minimised by a breadth-first search, seeking out all the spatially adjacent edges before moving to the next graph. Just conjoining the HGOld and the HGCurrent however leaves the location of the SHLink ambiguous. The horizon and shadow quads may not be at the ends of their respective lists and if they are moved to be adjacent in the new joint list, they will likely be no longer adjacent to their spatial neighbours.

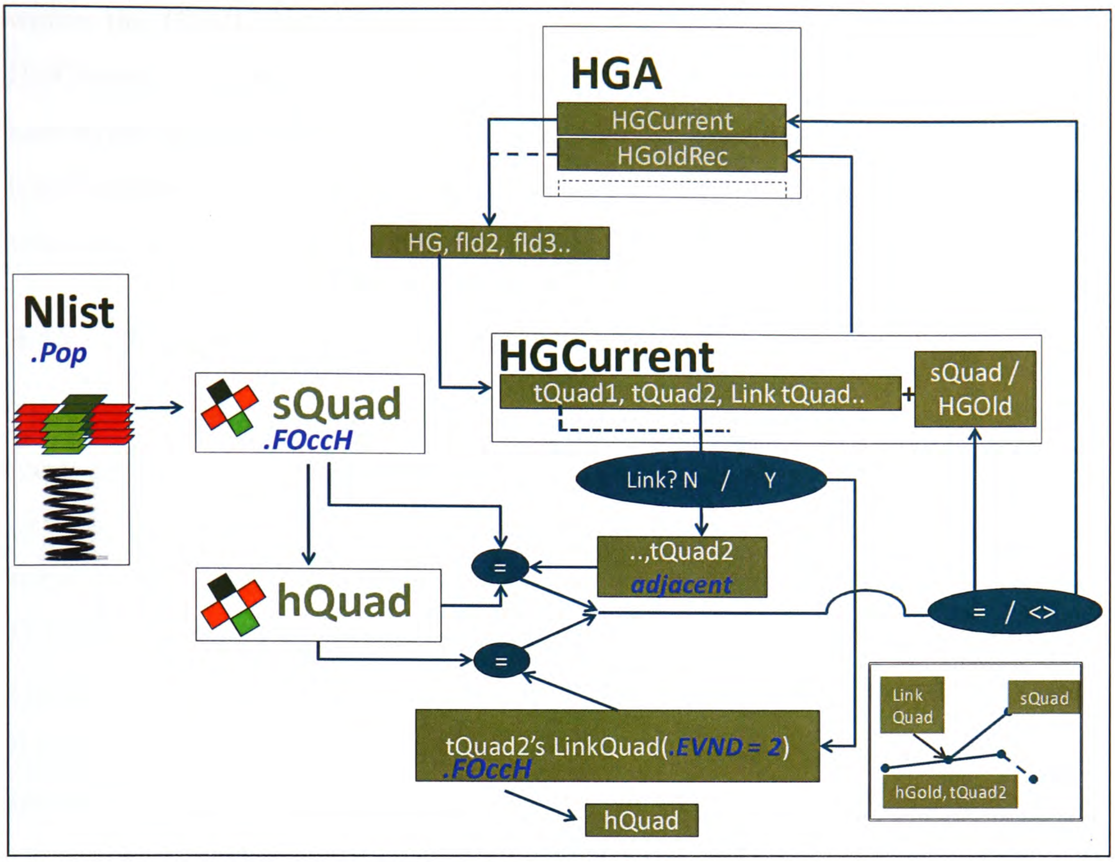


Figure 34 : Flow diagram for building horizon graph sets.

Both depth-first and breadth-first methods therefore appear to be $O(n^2)$ in time at best, and both fail to solve the problem of compressing multiple 2D graphs into a single 1D list. After trying variants of both, a method was developed starting from a breadth-first search (Figure 34). When a SHLink is found but no matching occluding edge has yet been found,a specially coded dummy tQuad is also added to the current mGraph (a 'LinkQuad' #40.233) which holds the **occluding** edge as its FOccH. The tQuad.EAtt.FEVND attribute is used to identify this as a Link node so when the HGA is scanned, its FOccH is compared instead of the main tQuad. In this way a reverse pointer from horizon **to** shadow is created only as and when needed for a scan to later identify if the test edge is an occluding mGraph edge and which horizon-graph edge it shadows.

The HLink plays a further important role. When a match is found in the HGA, the existing HGCurrent is interrupted. The HGOld is, in effect, being inserted between the occluded mGraph edge and any spatially adjacent mGraph edge sharing its remaining visible mesh node. As previously noted the SHLink partner will also be somewhere within the HGOld list of edges. After the testList edge has been added to the HGCurrent, but before the HGOld has been appended, a LinkQuad is added, identifying which of the edges in HGOld was the match the SHLink parter to the testList edge (#40.321). In this way 'T' junctions can be built in into the HGCurrent when the horizon graph branches.

4.15 Reading the Horizon Graph (hGraph)

The previous stage provides a list HGA, with one or more visually connected sets of mesh edges. However the horizon graph (Figure 33a) is still only implicit. Two types of horizon graph (hGraph) nodes need to be identified. End nodes (hENodes) where a horizon stops, and visual intersects due to occlusion (HSLinks in the mGraph). hLNodes need to be separately identified. This is because, while they are found spatially at one 'end' of an occluded horizon, they also visually split the occluding horizon in two. A number of these hLNodes may divide the same mesh edge into many hGraph edges. Alternatively, many mesh edges may form only one hGraph edge between a combination of hENodes and or hLNodes.

Each HGA record is dealt with in turn (#50.1). An intermediate list HGE is created to allow each edge to be tagged with attributes as to what its role is in the horizon graph. HGE.fldI carries the tQuad, HGE.fld2 carries a value relating to the number of hGraph nodes that mesh edge has. HGE.fld3 records whether the mesh edge has anhENode. HGE.fld4 records whether or not the mesh edge has an hLNode.

4.15.1 Horizon End Nodes (hENodes)

Three tests are used to establish if an edge is an end node. Firstly it is established, through rotation on the map, whether the previous edge is adjacent to the new edge (if so a binary integer variable 'SpatiallyAdjacent' is set from 0 to 1 (#50.21)).

Secondly other spatially adjacent edges are checked (again by rotation) as to whether they are part of the horizon graph using the 'isShadowEdge'[30] class. If the result is that both ends of the edge connect to other horizon edges spatially then it is part of a ridge so cannot be an end node (#50.22).

Thirdly the FOccH attribute is checked to see if the horizon is partially occluded by another edge (in which case one end is an hLNode, though the other may still be an hENode).

If no spatially adjacent horizon edges are found, or only found at one end and if the edge is also occluded and SpatiallyAdjacent is 0, then the edge has an end node. HGE.fld3 records the fact that the edge has an end node while HGE.fld2 has '1' added to its value.

4.15.2 Visual Link Nodes (hLNodes)

If the test edge has an occluding horizon, this is recorded in HGE.fld4 (#50.23). The tQuad of the occluding edge is then also added to HGE unless it already exists (#50.24). The hGraph node 'points' are divided between the two, i.e. 0.5 to fld2 of occluded and occluding edges respectively. Fld2 is only incremented if the relevant value in fld3 or fld4 is 0 to prevent double counting of nodes if the same edge is revisited due to a loop in the graph. This method of counting nodes will prove useful in identifying where hLNodes are crossed when reading the hGraph later to calculate the Euler complexity.[31]

4.15.3 Horizon Graph Edges (hEdges)

The HGE now explicitly holds the nodes of the hGraph, but its edges are still implicit. Two kinds of hGraph edges can be distinguished as to the method of their

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[30]isShadowEdge compares a tQuad with those held in PrjShadows, returning a requested value if found. It can also be set to draw the found edge in perspective using the co-ordinates previously stored in this list, which is useful for following the program.

[31]Various attempts were made to count how many times particular hGraph nodes and edges were traversed as the HGA is built but this proved unreliable.

identification. The first, are the hGraph edges made up from more than one mesh edge and which run between the mesh edges holding hNodes.

To count these, each edge identified as a node-holding edge in the HGE is taken in turn as a starting node (#50.3). The mGraph is navigated until another HGE node edge is found (#50.31). When a destination node is found, its HGE.fld2 is checked and if greater than zero the node has not yet been processed, so nor has any edge connecting to it. In this case the Edge-Node count is incremented by 1 (Rule 1; #50.32). The same procedure is then undertaken for the edges leading from the other end of the start node.

The second type of hGraph edge are those which fall within a single mesh edge. For example if a mesh edge occludes another mesh edge, it will have an hLNode which will divide it in two. This will be the node found via the mGraph and Rule 1. However if it has a second hLNode, or ahLNode and an hENode, then there will be a hGraph edge between these two nodes. These are accounted for via four further rules:

Rule 2 (#50.33): If the node is an occluded edge, i.e. HGE.fld4 = 1, then its fld2 has been given 0.5 to mark this fact. However, this node does not divide the occluded edge itself (or rather it divides the occluded edge between visible and none visible). This needs to be removed from the fld2 value before further processing.

Rule 3 (#50.34): One of the nodes in the hGraph edge will be the one from which edges found via Rule 1 begin, this also needs to be removed from HGE.fld2. Each hLNode has added 0.5 to HGE.fld2 and an hENode adds 1, but both have the same value in terms of their contribution to new hGraph edges. If an hENode is present, it is classed as the core node in preference to any hLNode. When the core node's value (i.e. 1) is deducted from the total HE.fld2 it is clear therefore that the remaining value is constituted by hLNodes only.

Rule 4 (#50.35): Increment EdgeCount by 1 for every multiple of 0.5 in HGE.fld2, deducting 0.5 each time until HGE.fld2 is 0. In this way once the hGraph edge has been processed, when it is found via Rule 1 from a different starting mesh-edge, it can be established that the common edge has already been counted.

Rule 5 (#50.36): If an mGraph edges has no spatially adjacent mGraph edges then it will not be recognised as a hGraph edge by Rule 1. If so and it has both an hEnode and an hLNode, then increment EdgeCount by 1.

4.15.4 Calculating the Euler Characteristic

The Euler Characteristic is then simply the sum of the values in HE.fld2 (collected before each is processed) from which the final EdgeCount value is deducted as below:

E = v – *e (where E = Euler number, v = vertex count, e = edge count).*

4.16 Tests

Testing was based on two general types of landscape feature, ridges and mountains, represented by simple pyramids. Ridges are useful as it is easy to establish predictable locations from which loops will be seen. Ridge data sets were constructed for E values of 0 to -5 (-5 being the lowest E (most topologically complex) image used for the survey in Section 5). Set 1 also contained a hanging end so as to ensure that horizon branches which do not form loops are also being correctly assessed. Set 6 uses simple rectilinear pyramids[32] because it is possible to predict what the view should look like, whether the topological links are in the right places and what the final Euler number should be. This introduces the possibility to test 360^{o} viewing position range, topology change between viewpoints, fine distinctions in the perspective geometry and multiple separate horizon graphs.

Set 7 repeats the same arrangement as Set 6, so results can be compared but includes non-rectilinear features, to ensure that the algorithms did not take advantage of some unanticipated effect of edges being aligned to the co-ordinate system. The results are still relatively simple so that the program could be tested from all viewing angles. Set 8 uses randomly located points with random heights, to further test that there are no unintended simplifications in the algorithms. Set 9 is topologically simpler, but using many mesh elements, and based on contour lines, as is often the source of real

[32] It was this dataset with which small number effects on the scan order were first noted.

elevation data. Set 10 returns to a randomised height field but with an (edited) background of random hills, testing if multiple horizons can be handled when both are complex.

Table 1 (appendix 3) provides a summary of the levels of complexity of each dataset, the Euler Character returned, and whether manual assessment agreed with this. The relationship between the complexity of the dataset and the complexity of the view is not straightforward. From some viewpoints the view from a complex dataset may be very simple, from others more complex. In the more complex cases it was often necessary to infer the horizon graph from the map of HSLinks, particularly because the perspective visualization often lacked the resolution to display very distant horizon loops. It is of course debatable whether the metric should not therefore take some account of the screen resolution and the acuity of the human eye.

In afew cases the horizon graph was so complex that it is very difficult to assess by eye or from the map if the result is correct. If there was any uncertainty as to the actual Euler number, but the predicted value was believed correct, the result is marked in Table 3 with double question marks ('??'). Where more than one horizon graph resulted, the respective Euler numbers are separated by semi-colons.

Finally, a large dataset is used. Since any real DEM[33] would need to be generalized and smoothed substantially anyway, this was generated artificially by interpolation of Set 6 using ArcGIS (Figure 19, Section 3, shows a perspective rendering in ArcScene and Figure 35 a viewshed and perspective in VoronoiMagic). It contains around 70,000 height nodes arranged into a variable height 'ridge' and separate 'mountain' with 'sea level' plains around each. This demonstrates that the software can run on a large dataset without any basic errors such as memory overflow and the resulting map contains no obvious errors, though it is too complicated to establish manually if the Euler value is correct.

[33] Digital Elevation Model is used when no specific model of the terrain is implied. Digital Terrain Model is used when a specific model (e.g. raster or triangulation) is referred to.

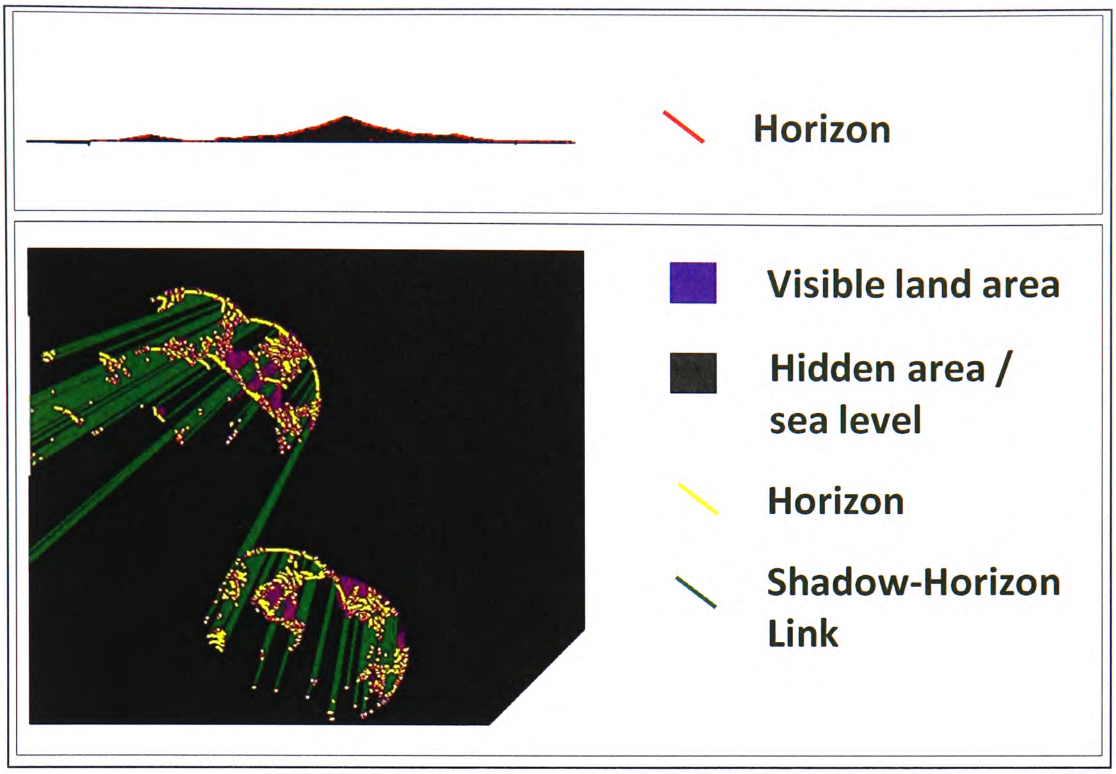

Figure 35 : Scene and viewshed output for a large simulated terrain.

4.17 Walking the horizons: Managing dynamic views and dynamic view points

One application of the method employed here, of potentially great interest, would be the possibility of reducing the processing required when calculating changes in a view. O'Sullivan and Turner (2001) attempt a similar idea via a series of topological matrices that state which pixels in a DEM are visible from which viewpoints. In this way, if the land cover at these locations should change, the view statistics can be quickly calculated. Visual Topology achieves the same end allowing the view to be quickly navigated via the SHLinks (green lines Figure 36a) and view statistics calculated. Thus if the more distant land in Figure 36 (a) changes from green to yellow (e.g. oilseed in different seasons) the cross horizon contrast and resulting patch complexity can be established immediately.

Unlike the visibility matrix however, the locations are still embedded in their spatial context and can be used both to predict when land cover changes will affect a view and reduce the processing required when a new occlusion is predicted. The horizons, shadows and hLinks serve as rough bounding extents (Laurini and Thompson 1999 p.

127) for initial testing as to possible visual relevance of changes. In Figure 36b any location above the dashed lines is visible, further Zone 1 is that between the viewpoint and the first horizon and thus visible, Zone 2 is space below a plane formed by the SHLinks (and thus occluded), and Zone 3 is an area between a shadow and a horizon (and thus visible).

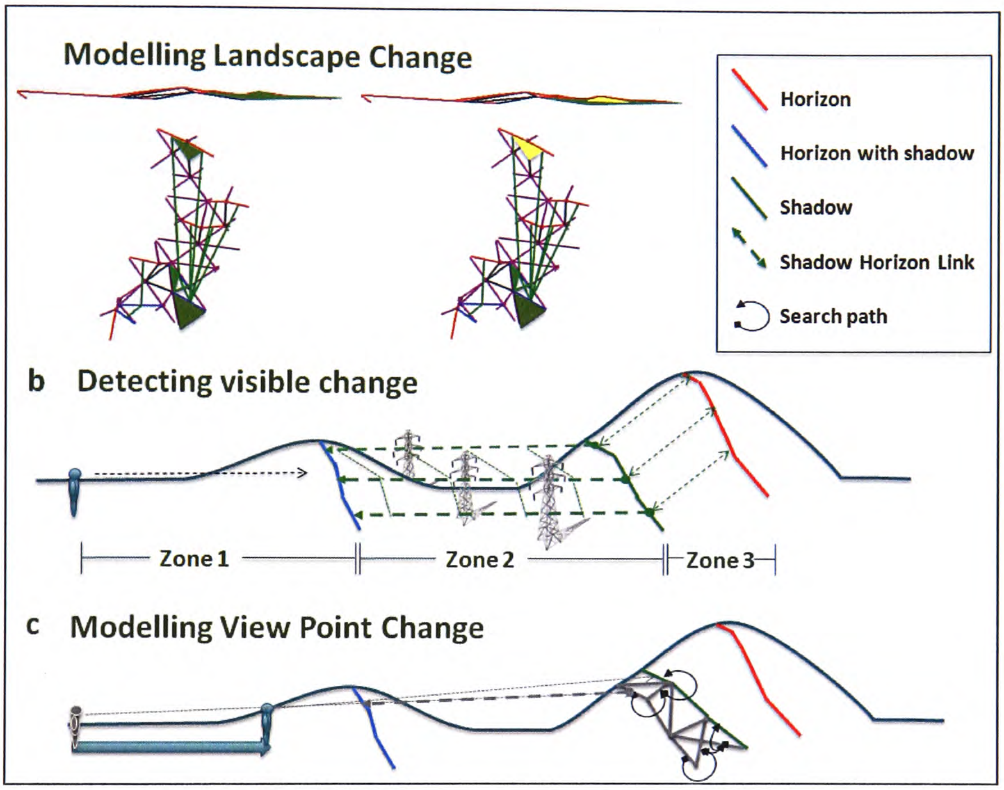

Figure 36 : Options for dynamic landscape modelling with Visual Topology in Delaunay TIN: (a) Changes in landscape colour or texture; (b) Changes in landform; (c) Viewpoint change.

These capabilities, combined with the qualitative advantages of reading the horizon graph itself, such as the ability to predict Euler Character, meet the original design aims. A more challenging opportunity, and one that was only briefly explored, is using the knowledge of the apparent horizons and the shadows they cast from one viewpoint to narrow the search for the same from a new, adjacent, viewpoint. It was realised that most often the new shadow will be close to the previous shadow, except where for example it crosses a previously occluded ridge. Instead of searching the entire DEM for the new viewshed, it should be more efficient to search outward from the previous shadow edge mGraphs until an edge is found that intersects with one of the horizon edges found from the previous location, as it is now seen from the new viewpoint (Figure 36c). Only if this failed to find a match would a new mesh wide scan be needed.

Procedure FormMain.WalkHorizon is an attempt at implementation. For simplicity only movement toward the view is considered, since lateral movement and movement away from the view brings new edges into the view that were not previously present, for the same reason it is also only effective on simple test data where movement toward the view does not produce large 'parallax' effects in the periphery of the view.

The procedure works from the list PrjShadows created to hold the visual topology during the last analyses (#26.02) this is put into a stack SList (#26.025). PrjHorizons is reset to receive the new horizons as they are found (#26.04) and SList iterated through (#26.05). Assuming that the existing SHLink does not also work for the new viewpoint, the direction of the movement is checked (#26.09) and a spatially adjacent mesh-edge put through mesh.EdgeProcessing. This will compare the new edge to the potential horizon edges known to be visible from the previous position. If none of the existing horizons from the previous position match, then the 'walking' scan moves the shadow edge to the next adjacent edge on the mesh and so on until a match is found (#26.2). Some search limit could be used to prompt a complete new scan.

This simple class allows the new location of the shadow to be found with the minimum of edges being considered. How large a saving in time might be achieved compared with completely re-scanning the mesh will depend on the precise form of the landscape and the path taken by the viewpoint. For incremental movement one could expect the saving to be large, while bigger steps would almost always require rescanning because of the likelihood of new ground becoming visible. Run in parallel with complete visibility analyses for staging posts along a predictable route (as might be the case with an in car GPS system for example) it should be able to undertake such processes in real time.

4.18 Conclusions

Section 3 concludes that the method can, theoretically, meet the application requirements set out in Section 1. The issue is whether the implementation of that method is robust and efficient, and what lessons should be learned from the process of building the software. To aid cross-referencing the section sub-numbers are used to specify conclusions to each stage of the process.

4.18.1 : Sections 4.2 to 4.11 (Scanning and graphic processing)

The case for the use of Quad-Edge TIN over other mesh structures has already been made and will ultimately be dependent on the application, platform and other technically standard decisions (as too will be the precise choice of algorithm for the graphics processing stages). That is to say, the choice of implementation at each stage does not move beyond boundaries of accepted practice, though segment based HSR may be more common in computer graphics than GIS. This said, a few relevant limitations in their implementation should be acknowledged and lessons learned.

The algorithm for transforming co-ordinate systems to that needed for projection is limited. A 3D pre-projection algorithm to replace the 'rotateview' class would make the software useful in a wider range of circumstances. However, there is no reason to believe that the properties of the resultant 2D scenes (the input for the topological algorithms) would be intrinsically different if a more comprehensive co-ordinate transformation were applied.

More generally, the limited GUI capabilities have made establishing effectiveness in the most complex scenarios difficult. This could be helped by using commercial graphic pipeline processes to display the scene, but as has been found, small variations in process can be significant so the scene rendered by, for example, a Z-buffer may not be quite the same as that processed by segment projection. The core components of VoronoiMagic have been successfully integrated with OpenGL previously (Gold, Chau et al. 2004) which would allow better rendering and 3D rotation of the output but time has not been available in this case. However, while GUI limitations mean that one cannot always be *certain* that the correct Euler

Character was obtained, some confidence may be taken from the fact that the correct Euler character has been returned in every test where it is possible to make a manual assessment. Nor is there reason for concern that errors would be perhaps more likely in these visually more complex scenes. Indeed topological complexity would not change[34] with increasing resolution or decreasing scale, which is one advantage of this method for mapping visibility. Furthermore, with smaller mesh elements relative to the landscape's scale, the number of spatial and visual topological relationships per mesh edge is likely to be smaller. Thus high resolution datasets are in some respects simpler tests of the algorithms than lower resolution datasets. In fact, the range of circumstances tested represent rather more exacting examples than are likely to be found in real landscape DEM, an area with comparable height variance to Set 6 for example would only be found in manmade environments.

It is notable that robust computation is essential when dealing with visual analysis since the effect of perspective produces very fine distinctions in position in a view, even from very coarse data. It is interesting to note that due to this, two different algorithms were needed for the scan, and two were needed for the Hidden Surface Removal. In both cases neither was perfect in all situations, rather one sufficed for the majority of cases but the second was needed to double-check results since it failed in different contexts. It is not clear how robust the computation would need to be to avoid such problems all together, but the literature on point-in-polygon operations would suggest that some form of double checking is always required.

4.18.2 : Section 4.12 (Horizon/Shadow links)

It is considered that this implementation demonstrates the utility of mapping visibility through topological links between horizons and their shadows. Further it shows that this process can be both robust and computationally feasible. The final map is far

[34] Issues of topology and geometric resolution discussed in Section 1 aside.

more efficient in terms of space, and richer in terms of the amount of information which can be extracted about the view. As such it represents a viable and fundamentally new way of thinking about and undertaking visual analysis in GIS[35]. Processing time could no doubt be improved substantially since this code has been developed as understanding of the problem progressed. In addition the lower resolution DEM might well suffice for modelling large scale problems and it may be possible to predict extents where visual topological events are impossible, in order to direct the process more efficiently.

The decision to only record one-to-one relationships between occluded and occluding edges, and so avoid the lists required to manage one-to-many relationships in reverse was valuable in that it establishes such a model can work (as the most memory efficient model). However, allowing a more complex data structure for the visual topology would allow multiple visibility maps to be held simultaneously. It would also make the Euler calculations simpler and more efficient. Given that computer memory is likely to become effectively unlimited in the foreseeable future (Fildes 2010) lists of visual links embedded into the mesh (or linked from a database) may well be the more useful model in the longer term.

4.18.3 : Sections 4.13-4.15 (Building and reading the graphs)

The key to building the horizon graph was the development of the Link tQuads and the HGA list. This allowed the program to connect the spatially separate horizon graphs on the map together as and when links were found, and to create Horizon to Shadow links when needed. In particular the Link tQuads made it possible to compress the 2D graphs into a 1D string and still be able to read the topology later.

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[35]De Floriani and Magillo De Floriani, L. and P. Magillo (1996). "Representing the Visibility Structure of a Terrain through a Nested Horizon Map, *International Journal of Geographical Information Systems*, 10, 5, pp. 541-562, Taylor and Francis, London.". have previously considered the use of horizons and shadows for mapping visibility, and use a similar method for their identification. They do not establish topological links between horizon and shadow however, be that embedded in the mesh data or as a connected table. Without the SHlink information one cannot quickly reconstruct the view, navigate the perspective view or dynamically model view change.

This process is very robust, correctly finding visually connected graphs while leaving separate graphs in separate rows of the HGA. It could no doubt be made more efficient since it presently requires several stages of list searches, in effect several passes over the horizon graph, to obtain the necessary information. One-to-many Horizon-Shadow links would remove the need for the LinkQuad, but the basic principle of maintaining a current graph and concatenating rows in a list when common edges are discovered is probably a fundamental recommendation for any similar task. Since only a small proportion of the mesh edges are involved in the horizon graph and only a fraction of these contain hNodes, efficiency is less of a concern during this stage.

4.18.4 : Section 4.15.4 (Calculating the Euler Character)

The Euler Character algorithm is robust as far as can be established from the test results above. To be certain of this one would need to test against the full parameter space of possible scene complexity. There is no upper bound to scene complexity as a whole, nor is there an accepted comprehensive model of component visual topological relationships such as the 9-Intersection model (Egenhoffer and Herring 1990) for spatial relationships. Rather the aim was to model and exceed expected natural horizon complexity, for which it is believed the implementation has been successful.

The power of Euler's equation is demonstrated in the simple rules for its computation. Attempts to explicitly construct and traverse the hGraph without resorting to a 2D geometrical representation had proven problematic until it was appreciated that this was not necessary – one only had to be able to count the nodes and edges. It also proved a valuable measure in helping to establish that the visibility map was correct when the mGraph was too complex to follow but the perspective view could still be interpreted.

4.19 Conclusions

Overall, the implementation achieves its aims as a prototype. Limitations identified are significant with respect to practical deployment, but do not cast reasonable doubt on the potential utility of the methods set out in Section 3. Remaining implementation issues could be resolved with generally available software such as OpenGL, although programming and time for user testing could still be extensive. Research questions remain in how to make the process dynamic under viewpoint change, such as how to include new horizons not visible from previous viewpoints. How to use the capabilities more fully is also an area to be explored. For example it is now possible to look at models of land cover change in perspective view and create feedback loops to subsequent change (e.g. based on believed likely public response). Alternatively it should also be possible to create monitoring algorithms to highlight when a sensitive view might be affected by development or identify specific households the view from which might be most sensitive. Since it has not been feasible to undertake such monitoring to date, questions are raised both as to what to look for, and then how to query this new data structure to find these features.

5 Section 5 - The Euler Character: A new type of visual landscape metric

5.1 Introduction

Landscape preference theories such as Prospect-Refuge theory (originally proposed by Appleton in 1975 – see new edition (Appleton 1996)), Kaplan and Kaplan's landscape preference matrix (1982; 1989) and theories of visual perception (Gibson 1986) propose that the physical structure of the landscape has a direct psychological effect on people due to evolved sensitivity to particular defining characteristics. Whilst the Kaplan and Kaplan matrix only qualitatively defines the dimensions of this, various attempts have been made to add quantitative parameters to landscape theory (Tveit et al., (2006) provides a review). Achieving a formal understanding of human landscape preference has potential benefits from more efficient and less controversial planning processes (Martinez-Falero and Gonzalez-Alonso 1995; Vanderhaegen and Muro 2005) to the design of landscapes for human health benefits (Velarde, Fry et al. 2007).

Efforts to identify consistent quantitative relationships between landscape metrics and human preference have had some success (Dramstad, Sundli-Tveit et al. 2006; Aalders, Ode et al. 2008; Ode, Fry et al. 2009). However the field has faced some criticisms. One is a philosophical argument as to whether identifying 'net' preference from a group of people is particularly helpful, arguing that group preference is a cultural, and therefore temporary, construct and not necessarily a good one (see Gobster (1999)). Another is that because preference rating tends to decline as the landscapes become more extreme (e.g. a salt flat or cliff face) results may simply demonstrate that a population tends towards a normal distribution and that this simply gives quantitative evidence for the a lowest common denominator (Lothian 1999). Therefore, the argument runs, it fails to provide a case for protecting unusual landscapes that serve the needs of minorities who do like extremes such as remote wilderness or modernist urban areas. There have also been problems with low explanatory power in the results (Palmer 2004), perhaps because people bring background knowledge to landscape interpretation including other sensory cues as to hidden landscape features so visual experimental stimuli do not include all the variables. Recent work, using environments sampled from one landscape type, has shown people may be able to adjust the scale of perception to the range of variance (Tenngart Ivarsson and Hagerhall 2008; Nordh, Hartig et al. 2009) which provides some counter to this criticism because the unexplained variance might yet be explained if the metrics themselves operated at multiple scales. Further, while Tveit et. al. (2006) argue that the aim is not to determine optimal landscape characteristics, rather it is to develop an evidence based framework for decision making.

More fundamental have been the criticisms that a) landscape metrics have not been able to establish globally applicable relationships (making experiments from different locations hard to compare) (Ode, Hägerhäll et al. 2010) and b) have been dependent on planar maps for the derivation of the metrics yet dependent on photographs for the preference data (Germino, Reiners et al. 2001; Sang, Ode et al. 2008). Photographs, being a perspective view both mask parts of the landscape, itself a factor in the ideas of prospect and mystery (Kaplan and Kaplan 1989; Appleton 1996), and change the apparent shape, size and arrangement of objects in the landscape (Antrop and Van Eetvelde 2000; Germino, Reiners et al. 2001). The effect of perspective is, for most measures, unique to a particular location; simply moving a few meters may drastically change the view. Opponents have argued therefore that metrics cannot model human experience of landscape because it is too variable, and this variance cannot be mapped.

Sang et al. (2008) indicates that human perception seems to be somewhat more sophisticated than simply reacting to a view. Since some preference data actually corresponded more closely to map metrics than scene metrics it may be that there is either some aspect of mental map-projection, or at least some robustness in landscape perception to perspective change. Nonetheless there are certain aspects of a view which cannot be captured from 2D map analysis, principal amongst which is the apparent horizons from different locations. Mapping the variance in metrics as perspective changes may be extremely difficult, but it is not impossible. The mathematics of perspective are well understood. Provided a change in perspective does not produce new occlusions, or bring previously occluded areas into view, the change in relative area and shape from one view point to another is predictable (Tarr and Kriegman 2001), and can therefore be described statistically. The difficulty lies in identifying when significant changes in the level of occlusion will occur or, to look at the problem another way, what is noticeably invariant in a sequence of scenes. This is something Machine Vision uses as a basic principle of scene recognition (Hogg 1993, Rosenfeld 1996) and is believed to operate in human vision also (Tarr and Kriegman 2001; Kimia 2004).

Section 2 proposes a metric of visual complexity that is invariant to local changes of view point, being based on the topology (Kinsey 1991) of the graph of the horizons in a view. This Section reviews and extends that argument as to why topology might be relevant to human landscape perception before presenting the results of an experiment to test whether the specific metric proposed (Horizon Graph Euler Character) has cognitive significance. It investigates if images with higher horizon graph complexity were considered more interesting than those with lower graph complexity, and if so whether that interacts in some manner with geometric complexity, as was suggested may be the case by Ode et al. (2010). All the images used are provided in appendix 4[36].

5.2 Utility of topological metrics

As previously stated, topology is a branch of mathematics which deals with the order, rather than the scale, of things (Kinsey 1991). Topology is often fundamental to function. For example, a deep canyon cannot be crossed on foot without a bridge connecting the two sides, regardless of whether it is 3m or 300m wide, just as landscape patches need suitable green corridors in order to form network habitats (Bell 1999, p. 212). Topology is a discrete pre-condition to some functions.

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[36] The survey is available online at www.odelandskap.se/intro.aspx.

5.2.1 *Shape and perception*

Topology is also fundamental to shape and human perception of space. For example, a Pyramid, a Cube and a Sphere are all fundamentally the same from a topological point of view ('homeomorphic'), whereas a doughnut is different. People naturally perceive this difference in character (Mark and Egenhofer 1994; Antrop and Van Eetvelde 2000; Mark and Turk 2003), while Topology mathematically measures it using Graph Theory (Kinsey 1991). Cubes and pyramids are both the same topologically because they can be stretched one into the other without edges crossing (see Figure 7 of Section 2). In creating loops, the lines gain semantic structure which simplifies the picture. Rather than a wire frame of 8 points connected by 12 edges one can see 6 sides, or simply 1 volume. Visual Topology interacts with this effect, since intersections may also occur that are only apparent due to the angle of view (Tarr and Kriegman 2001). Figure 37 demonstrates how the inherent topology and geometry of an object influences the range of visual topologies that are available. The two 'vertices' highlighted in figure 37 (a-i) are the result of the shape of the object and the viewpoint in combination. Figure 37a also demonstrates how people can naturally perceive higher dimensional topological structures, so topological 'complexity' can add semantic structure to geometric complexity (Ode, Hägerhäll et al. 2010).

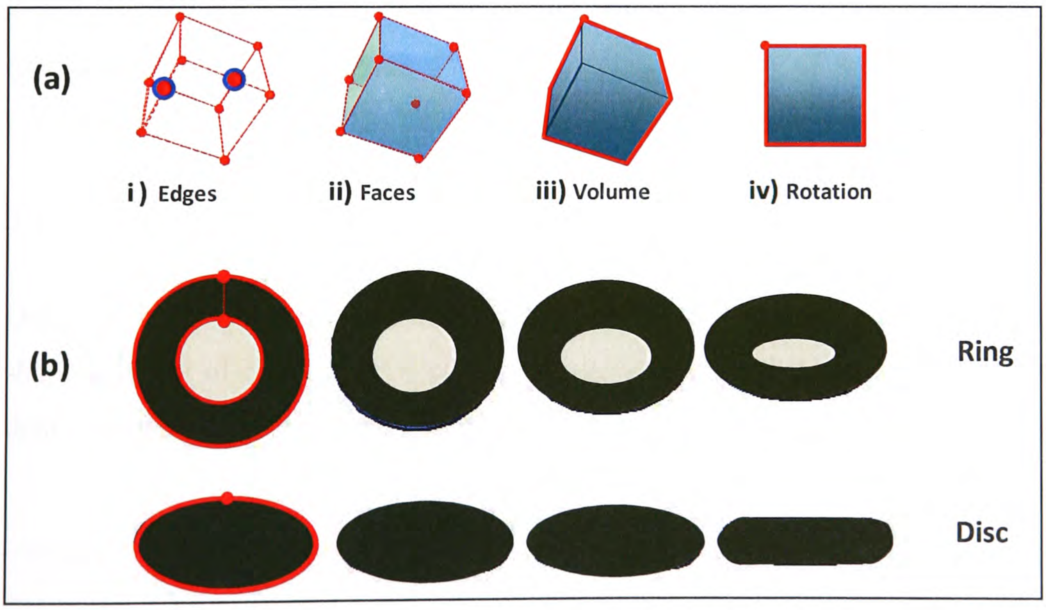

Figure 37 : (a) Effect of apparent topology in simplifying perception of complex wire frame (b) Effect of rotation on the apparent topology of a torus.

Topological relationships are more commonly used to describe spatial relationships in human language than metrics such as polar co-ordinates (Mark and Egenhofer 1994; Mark and Egenhofer 1995) and have long been implicitly understood in art (M.C. Esher for example (Schattschneider and Emmer 2003)) and landscape design (see Lucas (1991) on focal views (p.82) or the sensitivity of ridges (p.231)). The field of machine vision uses concepts of visual topology extensively (Plantinga and Dyer 1990). However, in environmental psychology, despite the wide recognition of humans' need to "understand the way the landscape is assembled" (Bell 1998 p.48), and key theorists' emphasis that people focus on the connecting or bounding edges of landscape (Appleton's (1996) 'vistas' structured by horizons, Marr's 'primal sketch' (Marr 1982), Gibson's confluences of 'optic flow' (Gibson 1986)), the mathematics of topology has yet to be commonly seen as a fundamental aspect of landscape perception. Other than through metrics from landscape ecology such as the contagion index (McGarigal, K. et al. 2002), topological indicators have not been much used, yet once understood, topological complexity is easy to measure because it is discrete and unambiguous[37]. It has fundamental units, and does not depend on qualitative classifications like broader concepts such as 'roughness' nor defined measurement scales as do metrics such as shape indices (McGarigal, K. et al. 2002). The topological complexity ('Euler Character' (Kinsey 1991)) of the cubic volume in Figure 37a is described by the Euler-Poincaire equation (see Equation 3, Section 2).

5.2.2 Stability under local perspective change

One can think of a view onto the landscape in the same way as for the geometric shapes, except of course the object is so large only part of it can be seen. So rather than considering the graph of the whole object one only need consider the 2D graph

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[37]In theory. as will be seen from the survey below; in practice perceived topology is not always so clear cut, see also the work by Tarr and Kriegman Tarr, M. and D. Kriegman (2001). "What defines a view? *Vision Research*, 41, pp. 1981-2004."..

that is formed by those horizons which can be seen[38]. This can be described by a simpler version of the Euler-Poincare equation[39] ;

Equation 9 $$\mathbf{E} = v - e\,.$$

(E = Euler Character, v = vertices, e = edges)

This graph has no 'real' existence in the landscape, it is only a visual effect from seeing occluding horizons from a particular viewpoint. The horizons themselves can be mapped, but there is no physical point on the ground where two intersecting horizons physically meet, hence the term 'Visual-Topology' (VT). Nonetheless, the Euler-Character of this graph (E) is no different to the concept in any other context. 'E' provides an index of the number of loops in the graph, and therefore how many spatially distinct regions there are in a view or, conversely, how many occluded areas there are.

As with the example of the bridge, these are discrete measures, a loop is either present or not. If the point of view changes a little, usually the shape of the graph will change, but the number of loops remains the same. Occasionally a threshold is passed whereby a loop is no longer visible, or a new horizon appears (Figure 37b). This means that there are also areas on the ground within which perspective change produces smooth, statistically tractable, changes in landscape metrics[40] and so lines can be drawn on a map, the crossing of which introduces new, spatially distinct land areas into the view (or removes existing units). Sometimes one area may disappear from view as another comes into view. Thus there are also larger groupings of these areas wherein the net topological complexity is invariant, and lines on the map across which it suddenly changes (Figure 9, Section 2). The concomitant of this is that within

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[38] Which is helpful since the Earth is not a convex polygon, so Euler's theorem would not apply to the Earth as a whole.

[39] Equation 1 from Section 2, reproduced here for convenience.

[40] Not all metrics would be smooth; proportion of different land covers within a given area could still change in an unpredictable way for example, though this can also be modelled by building the land cover polygons into the topology graph.

these areas one aspect of perceived complexity (the number of depths of view and horizon edges for the brain to assimilate), is also invariant. Section 2 formally defines these 'Euler Zones', the aim here is to establish if landscapes seen from within Euler Zones with different E are perceived differently.

5.2.3 Horizons and landscape theory

Some landscape preference theories have taken a functional (evolutionary) perspective on human appreciation of landscape features and landscape structure. In both the Prospect-Refuge theory described by Jay Appleton in 1975, (see the 2nd Edition: (Appleton 1996)) and later in the matrix of factors predicting landscape preference by Kaplan and Kaplan (Kaplan and Kaplan 1982; 1989) the promise of visual access to new information is highlighted as one very important factor for landscape preference. The concept of Prospect in Appleton's theory is very similar to the concept of Mystery in the Kaplan's matrix; a similarity explicitly referred to by the Kaplans themselves. "In the case of prospect, the connection is straightforward. Prospect, by ensuring visual access to the surrounding environment, suggests a setting in which learning can take place. It thus provides a striking parallel to "mystery" (Kaplan and Kaplan 1982 p.91). There seems to be a particular attraction to that which we cannot see from our present vantage point, triggering human curiosity and need for exploration. Landscapes with prospects and mystery are, in both theories, illustrated with strikingly similar images/scenes, so called deflected vistas, often showing a bending road or a river leading the eye further into the scene; and if one could have entered the scene one could have experienced what is around the next corner. Of particular interest to this study is that Appleton also specifically talks about the horizon. "The contemplation of a horizon therefore directs the attention particularly to speculation about what lies *beyond* it, and the horizon itself seems to be the key which can provide the answer to such speculation. Potentially, therefore, the horizon has a major role to play in the imagery of the prospect." (Appleton 1996 p.80-81).

As a measurement of occluding horizons, the concept represents a progression from existing theories of landscape perception. The Kaplan and Kaplan (1989) landscape preference matrix suggests a parameter space, but it does not provide a means to measure this. Subsequent studies using metrics of planar maps are limited as to how they can represent occluded areas, while studies of perspective images have usually focused on more general contrast segmentation and those for which horizon depth has been the key interest, found identifying and segmenting images difficult to achieve (Bishop, Wherrett et al. 2000). The process of Euler Characterisation proposed here is one which provides a clear theoretical definition of the phenomenon measured and can be automatically modelled directly from digital elevation models, as demonstrated in the previous Section. Practical and theoretical benefits of VT as a metric not withstanding, can clear evidence of its relevance to landscape perception be established?

5.3 Method

A survey was carried out via the internet and at a University open day (SLU Alnarp, Sweden, May 2009). Internet respondents were recruited by 'chain referral sampling' or 'snow balling'(Biernaki and Waldorf 1981), that is by sending e-mails to contacts in the first instance who are then asked to forward the link to the survey website. The method is effective in quickly reaching a sizeable number of people but it does not provide a statistically representative sample of the population. The significance of this for analysis will be dealt with in the discussion section (5.5). Respondents from the University open day were also self selecting, in that a stand with information about the project was provided along with a computer through which to access the survey, no incentive or approach to respondents was made and the survey itself was not discussed with respondents (beyond the information provided on-line) until after its completion. The survey responses are completely anonymous, including as to whether they were made via the internet or at the open day.

After completing a short questionnaire to establish basic demographic and professional background, the respondents were presented with pairs of pictures and asked to select the picture they found the more interesting by clicking on the relevant image. Image pairing was fixed and the pairs were presented once each in random order.

The option of using simulated landscape images was considered, given the advantages already discussed in terms of controlling the content of the images and exploring the parameter space. However, the primary aim of the survey was to demonstrate that horizon graph topology was a salient factor in visual perception, not only of highly abstract forms but also of complex landscapes where many other features might serve to distract, over-whelm or otherwise obfuscate its effect. Visualisations are necessarily also simplifications and so open to the criticism that reducing complexity may emphasise the variable of interest. When the perceptual salience of a landscape characteristic has already been established in other studies, a more focused survey may help understand the form of its response function. Since no such prior studies existed in this case and the concept of the Euler Character was, by definition, rather abstract, it was considered that the concept would be more likely to be accepted as relevant (e.g. to landscape architecture and environmental psychology), if its perceptual salience were demonstrated in real photographs. None the less it is accepted that the use of real images undoubtedly introduced some limitations to the survey in terms of the range of Euler number that could be covered and as will be discussed in the results, it is believed that in some instances the attempts to control extraneous detail may have impinged on the representation of the topology itself.

Highly similar images were used in each pair in order to isolate the variable of interest. In addition to the primary variable of Euler character, it was also considered valuable to include a dimension for geometric linear complexity as this was expected to co-vary with Euler character, in the sense that scenes with many horizon layers are also likely to have more mountainous ('rougher') topography. This roughness aspect was also assessed for each image, as will be presented further in section 5.3.2. Although image pairs might differ significantly in character, no comparison between image pairs was requested and random ordering should remove any risk of a prior image pair prejudicing responses. In so far as possible, images contained very few cultural details, such as buildings. This was partly achieved by taking some images on misty mornings in order to obscure detail and focus attention on the horizons. Photoshop was also used lightly, to reduce any interesting cloud effects. In the case of image 21 a horizon was artificially added as no suitable image pairs were obtained. The complete image set is given at in Appendix 4.

5.3.1 Euler Character

The first test involved six pairs of images with the same roughness classification, either high (lots of height variation and jaggedness in the horizons) or low (smooth horizons with little height variance), but with an Euler Character differing by 1. This was intended to indicate whether there was an effect with just one horizon loop difference, and then whether any such effect weakened as the proportion of the total number of horizon loops in the image which that difference represented declined from 1/2 to 1/6.

The second test contained images with the same roughness classification but an Euler character differing by 3. As very few viewpoints gave an Euler number as low as -5 or -6, this was only available for three image pairs. This was intended to show whether a stronger response was found for a large difference in number of horizon loops.

As a control, a third experiment was done, whereby each image had the same Euler character as its partner, but one was classified as 'low roughness' and the other 'high roughness'. This was intended to establish whether or not any differences in the strength of response found in the other two surveys was due to the image pair being of low or high roughness and to establish whether a survey looking at the interplay of the two dimensions (after (Ode, Hägerhäll et al. 2010) might be merited. This provided 14 image pairs in total and took less than five minutes to complete.

5.3.2 Roughness

Ode et al. (2010) proposes that Landscape Preference research needs to be developed with a framework in mind where by potential new landscape metrics are tested not only in isolation but also with regards to other landscape characteristics. In particular, the parameter space between any two metrics needs to be explored to establish how dimensions interact. This allows the use of separate metrics to construct more meaningful models, and ultimately build an evidence base for semantic models such as the matrix of factors predicting preference proposed by Kaplan and Kaplan (1989).

In the case of horizon graph complexity there are two dimensions along which it might vary. One is the topological complexity, which is measured using the Euler Character due to its wide application and sound theoretical base. The other is the geometry of the edges. This can be further split into shape characteristics – sinuosity (i.e. how wiggly a line is), angularity (i.e. how sharp the turns are) and fractal index (i.e. cross scale self similarity). All of these are quantitatively definable characteristics, and so can, in principle, form a parameter space with the Euler Character. However, their measurement is less objective since various metrics can be applied, and may also require choice of scale and classification which affects results.

To ensure a short time period for completing the questionnaire, there were only a limited number of image pairs which could be presented. An index of sinuosity and angularity cross-tabulated with the range of Euler numbers would have produced too many options given that the primary goal was to first establish whether Euler Character (E) had any cognitive significance at all. A full investigation as to the interaction of Euler Complexity and Geometric Complexity would require a specific survey if E proved significant. None the less, geometric complexity remained a potentially confounding factor. Some decision would therefore be required as to how to classify the images with regards to geometric complexity.

A simple solution was developed whereby all images collected were classified from 1-5 according to horizon 'roughness', as a qualitative concept including both sinuosity and angularity (though not fractal complexity). Images classified 1-2 were then re-classed as having 'low roughness', and 4-5 as having 'high roughness'. This was a compromise between objective rigour and pragmatism as regards the range of images available and the limited literature for how to objectively classify images by perceived geometric complexity. Omitting the images ranked '3' for roughness improved the likelihood that the two groups of images would be reasonably distinct. Reducing the problem to two strongly differing classes also improved the possibility that any effect on response would be strongly evident. This still left potentially 12 more image pairs for the survey. It proved impossible to find a broad range of Euler numbers within each of these classes, since low Euler numbers also tend to occur with rougher terrain. So rather than a complete matrix of roughness and Euler number, it was decided to vary the roughness between images and keep the Euler number constant, which could be achieved in 6 image pairs[41]. This method does not, therefore achieve a full exploration of the parameter space between Euler character and roughness, but it does provide a means to limit roughness variation in the first two experiments, and explore something of the interaction between topological and geometric complexity in the third experiment to indicate whether further exploration would be merited.

5.4 Results

A total of 168 usable responses were received, Table 1 shows the breakdown by the demographic questions asked[42]. Unfortunately an initial mistake in the survey[43] meant that the first 27 of these respondents received one incorrect image pair (Pair 4), and so the adjusted figures are shown for this image pair in parentheses in Table 1. Since each image pair is independent the other responses are valid, but the error statistics pertaining to image pair 4 (Euler Number = 1 or 2) are slightly higher as a result. Specific error margins are given with each result and figures for this question are clearly distinguished by a different colour in Figure 38, they are also rescaled for visual comparability. The full responses for this subgroup are given in Figure 39, showing very little difference to the full set.

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[41] The scale of E runs from 1 to -5, however there is no image pair E = -4 as no suitable image pairs were available with low and high roughness.

[42] The sharp eyed may note that some rows only sum to 167 or 139, one less than the respective totals. This is because not all survey respondents completed all demographic questions. Since the main analysis does not make use of the demography, these are considered valid responses. The omissions are too few for any one factor to have affected the REML analysis. Insisting on complete demographics may have resulted in non-completion of the survey itself.

[43] The same image was presented twice in a comparison pair.

Table 1 Response Rates to Landscape Survey

All			
168 (140)			
Age			
Under 30: 22(16)	*30 – 50:* 104(89)	*Over 50:* 41(35)	
Gender			
Male: 70 (56)	*Female:* 97 (84)		
Do you work with landscape issues?			
Yes: 61(53)	*No:* 106(86)		
Do you regularly visit rural areas for recreation			
Yes: 139(114)	*No:* 28(26)		
Would you describe yourself as living in an urban or rural area?			
Urban: 109(93)	*Rural:* 59(47)		
Area of Residence			
UK: 50 (26)	*Scandina-via:* 94 *(93)*	*Continental Europe:* 15 (12)	*Other:* 9 (9)

It is not possible to accurately estimate how representative these figures are of the demographics of the respective populations. There is some bias toward female respondents, which has been shown to be relevant for studies of perception of safety in closed landscapes like woodland and parks (Jorgensen, Hitchmough et al. 2002) and may have some influence in broader landscapes also, though the nature of this is unclear (Ode, Fry et al. 2009). Two thirds of the respondents do not work with landscape issues professionally. This balance needs to be born in mind as other work has shown differences in opinion between those with professional experience and other respondents (Miller and Morrice 1995; Ode, Fry et al. 2009). That a third of respondents have some professional landscape experience is probably disproportionately high, but the images used in this study have little to distinguish between them in terms of management or 'naturalness' about which professional knowledge might be expected to influence opinion. In addition, the question asked is simply which are more interesting, not the more complex idea of preference[44].The

[44]Sevenant and Antrop Sevenant, M. and M. Antrop (2010). "The use of latent classes to identify individual differences in the importance of landscape dimensions for aesthetic preference, *Land Use Policy*, 27, 3, pp. 827-842.". do not find either profession or gender to be significant in their study of the influence of demographic grouping on aesthetic preference so the precise question and experimental design may well influence the significance of such effects.

responses are mainly from the UK and Scandinavia, with some input from (mostly north) continental Europe, and scattered responses from the USA, South America, Africa and Japan. In this context the proportion stating they live in a rural area is probably higher than the norm, though the picture is complicated by differing definitions of urban between countries and likely cultural differences in self-perception of this also.

Demographic questions were intended only as a basic check for confounding factors. Given the sample size in many of the sub-categories, it was not considered valid to look at multi-logistic regression across questions for demographic subgroups. Doing so would also imply some wider representative significance of the differences found between these groups, which would not be justified without a stratified random sampling method.

The UK-Scandinavia focus also sets a particular context as regards the kinds of landscape respondents are used to seeing. However, as the choice is between very similar images of the same landscape, not between different kinds of landscape, there is little opportunity for cultural influence on the decision. This is evidenced by the fact that a REML (Winkel, Saegert et al. 2009) analysis of the results with regards to the personal information collected about respondents, including the Area of Residence groups, did not find any statistically significant trends (see Table 2)[45].

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[45] (These results can be compared against a table on http://www.biokin.com/tools/fhint.html to see if statistically significant. None of the groups are shown to be significant.)

Table 2 REML Analysis of Results for Online Survey

Sequentially adding terms to fixed model

Fixed term	Wald statistic	d.f.	Wald/d.f.	chi pr
Question	46.14	1959	0.02	1.000
ImageID	156.48	14	11.18	<0.001
ImageID.LandProf	20.30	28	0.72	0.853
ImageID.Organisation	21.80	14	1.56	0.083
ImageID.MaleFemale	10.34	14	0.74	0.737
ImageID.Age	47.65	42	1.13	0.254
ImageID.Country	30.05	56	0.54	0.998
ImageID.UrbanRural	12.94	14	0.92	0.531

Dropping individual terms from full fixed model

Fixed term	Wald statistic	d.f.	Wald/d.f.	chi pr
ImageID.UrbanRural	12.94	14	0.92	0.531
ImageID.Country	31.30	56	0.56	0.997
ImageID.Age	51.18	42	1.22	0.157
ImageID.MaleFemale	13.63	14	0.97	0.478
ImageID.Organisation	29.75	14	2.12	0.008
ImageID.LandProf	28.02	28	1.00	0.463
Question	162.16	1959	0.08	1.000

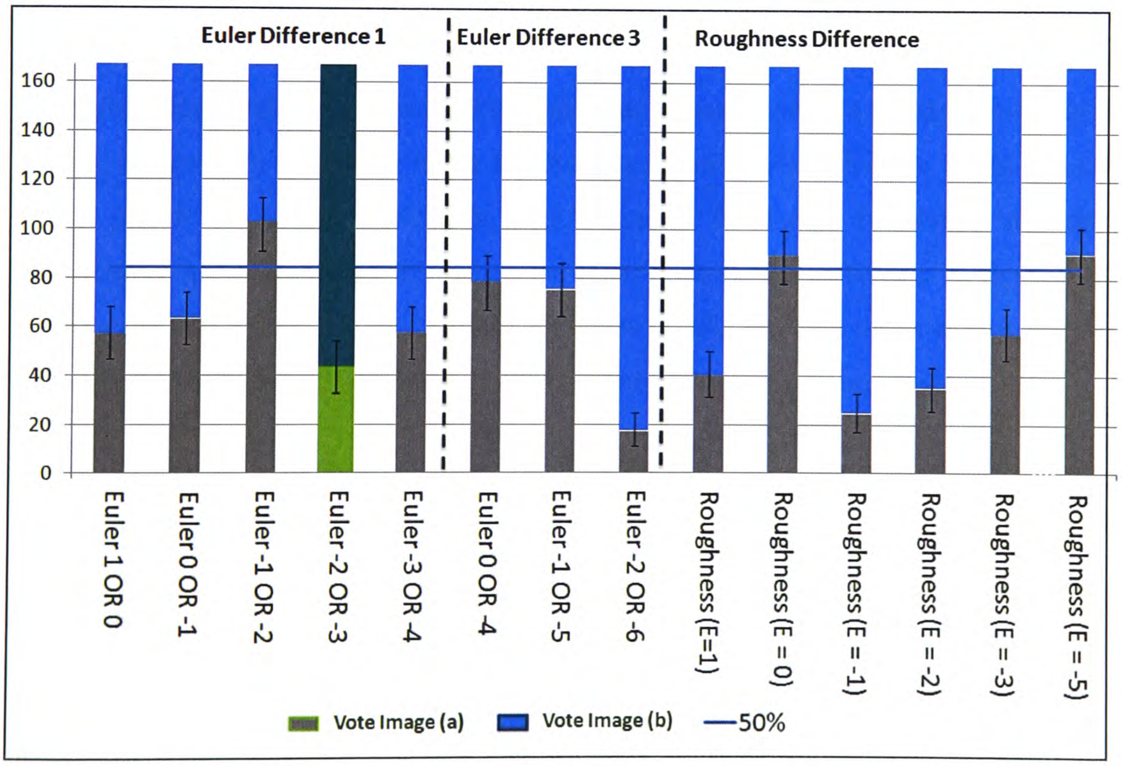

Figure 38 : Absolute number of votes for each image by image pair

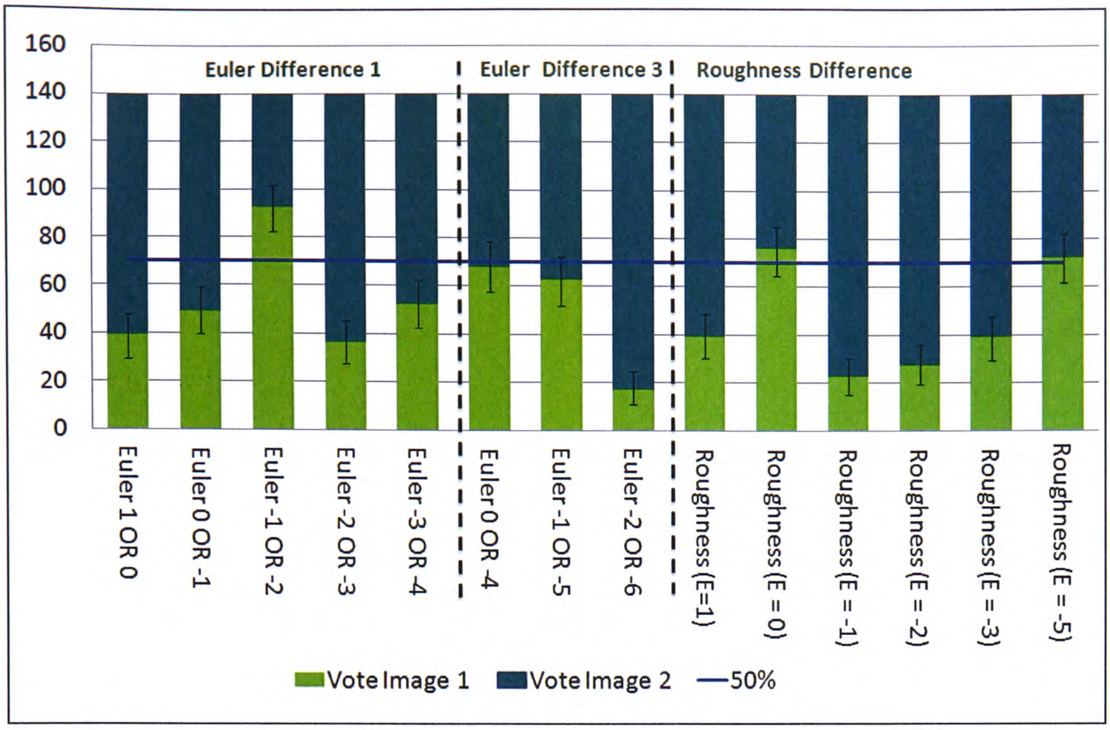

Figure 39 : Absolute number of votes, 140 subset with correct image pair 4.

The first notable impression from the results in figures 38 and 39 is that seven out of the eight image choices where the Euler number varied showed a majority preference for the image with the lower Euler number (i.e. more horizon loops). In the case of image pair 6 this is not significant, and for pair 7 is of only borderline statistical significance at 95% confidence, but in the other 6 cases, the difference is significant. In the case of the first section, 'Euler Difference 1' this is also a majority consistently around 60 to 65%, regardless of the total number of horizons in each case.

Although this may be due to some other unknown demographic factor, the results shown in Figure 40 suggest a general variation in preference over the population as a whole. The 65% split is not an entirely random selection of individuals for each image pair, roughly 18.5% of (140) individuals selected the higher E value images the majority of the time. Only 18.5%[46] of respondents (of 140) returned 50/50 responses as regards the E-value of the images they selected so E-value does seem to be a strong

[46] The precision of the similarity in two 18.5% groupings is likely to be just a coincidence, reflecting the fact that a likely Poisson distribution in voting preference of voters is being forced into just 8 image pair responses.

stimulus. It does not seem, however, that one will be able to 'please all of the people most of the time,' as there are opposing preferences. The distribution in preference between those (almost) entirely favouring the higher E-value image and entirely favouring the lower E-value image is polynomial. Therefore, the results for image pair 3 (E = -2 and E = -3; Figure 38) are in marked contrast. Some plausible explanations are discussed below which might be an important caveat to predicting the E-value from DEM.

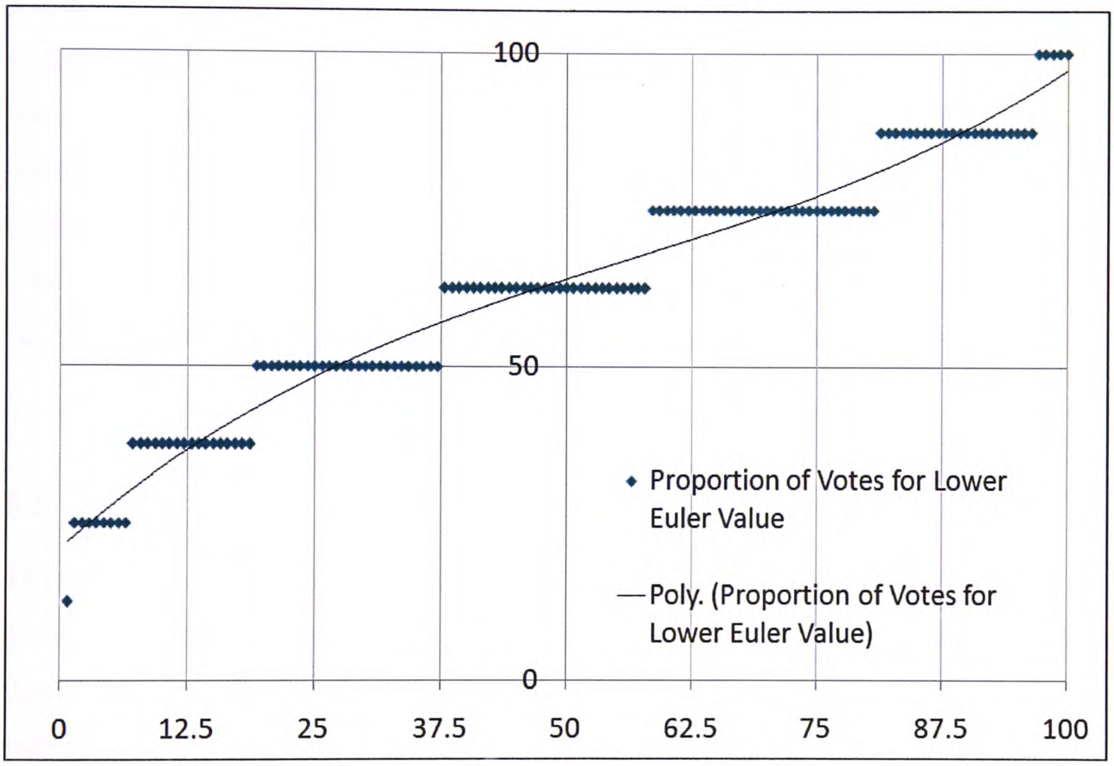

Figure 40 : Proportion of voters who cast a given proportion of their votes for the image with the lower E value.

The second part in figures 38 and 39, 'Euler Difference 3', is harder to interpret. The statistical power of the difference between 'Euler 1 or -2' and 'Euler 0 or -3' is weak, although there is a dramatic difference for 'Euler -1 or -4'. There are too few data points to be confident as to whether there is an exponential trend or the first two pairs simply failed to produce a significant preference. However, there are two reasons to suspect that there is an exponential trend. Firstly, it would be strange to see such a strong and consistent result for the relatively minor difference in 'Euler Difference 1' and yet little effect when the Euler difference is three times greater. Secondly, an exponential effect of Euler character on perception would be consistent with the result from the 'Roughness difference'. Further consideration of this is presented in the discussion section.

The 'Roughness Difference' results contain one clear outlier, 'Euler = 0', given that the result is also not statistically different from random, this result is not likely to be due to some specifically different process but simply that the stimulus was insufficiently strong. If that result is discounted as invalid[47], the remaining five results produce an interesting trend. Roughness is initially highly significant in determining voting with the 'rougher' image being considered most interesting. As the Euler number increases this effect decreases. Furthermore, the relationship is smooth and (assuming the missing value would not indicate otherwise) probably fits part of a curve. Thus it would appear that while the more complex image in general is considered to be the more interesting, the dominant source of complexity to which people respond changes consistently as topological complexity increases.

5.5 Discussion

That the majority of survey respondents tended to find the lower Euler number (i.e. more loops) images more interesting was expected and serves to confirm the general thesis that visual topology does have some effect on perception. The contrary indication from image pair 3 is in some ways more interesting. To seek some possible explanations, respondents known to the author (the responses to the survey being anonymous so untraceable for follow up) were asked which image they thought was most interesting and why. Contradicting the survey responses, these individuals actually preferred image (b), citing the play of the light in the sky, yet if this were so the survey should have shown an unusually favourable response to that image.

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[47] The question is still useful since it suggests that the attempt to remove other factors which might influence preference was successful, producing no preference when the intended differences were too weak.

One respondent who did favour image (a) commented:

"..Here the mountains are slightly lower, soft curves, hills have vegetation (or at least I can see them!)."(Anonymised)

The implication being that the other image was too obscure to see much detail, so one hypothesis could be that image (b) in pair 3 had too low a contrast for the topology to be quickly interpreted by respondents. When asked to give a more considered, verbal, response on two images, factors such as scene lighting were significant. However, when clicking through the survey, the ease of interpretation was more important. The image being so hazy also meant that the horizon-contrast was weak, so it may have been unclear to respondents how many horizons there were. Tarr and Kriegman (2001) show edge contrast to be indicative in speed and accuracy of image interpretation so this is an important indication of nuance for any attempt to model Euler character automatically; the method used must provide the possibility to factor atmospheric conditions and cross-horizon contrast into the equation.

Images with more horizon loops were considered more interesting. It should be acknowledged that spatial autocorrelation would generally imply greater land cover richness and scene diversity from spatially separate pieces of land, and thus might co-vary with topological complexity. However scene diversity was highly variable across image pairs. Image pair 2 showed the same degree of impact although the only significant change is the introduction of a little more near ground vegetation, as did image pair 6 although land cover richness is, arguably, lower in the more selected image. The total area change also varies considerably between image pairs. This implies that the causal factor is discrete, but is it simply the addition of particular types of land cover? There are some well known examples from environmental psychology of particular types of land cover having discrete effects, for example the presence or absence of water is affects preference regardless of the scale of that area of water in the view (Dramstad, Sundli-Tveit et al. 2006). Presence and absence from the view is mediated by horizons (Appleton 1996), but in some cases the distant horizons were so misty hid difference in land cover type. The strength of the effect was also apparently related to neither the length of a new horizon[48] nor the total number of horizons.

It seems that a variety of occlusions is itself a source of interest, and not just a mediator of land cover richness. This supports concept of mystery as each loop represents a separate set of occluded land. There is more diversity of occlusions, so more to stimulate human curiosity, and more locations than might be revealed by a change of perspective. With multiple occlusions, no single change in perspective (apart from straight up) will reveal all, but rather just more mysterious occlusion. Like a magic trick or a good thriller, the solution may frustrate but revealing it would spoil the fun!

One challenge to this theory would be that one very low contrast horizon had no effect, suggesting contrast rather than occlusion was the key factor. If so, then this study shows little variance between pairs given that some show bright sunlight and strong contrasts while others only vague contrast. This is a valid question to be investigated, but evidence so far would suggest the effect is discrete provided the contrast is sufficient to be noticed. That would concur with Tarr and Kreigman's (2001) conclusion that human perception is both qualitative (topological) and quantitative (dependent on extent of geometric change and the limitations of human edge detection). Another challenge is the evidence from the 'Euler difference 3' data.

5.5.1 Euler difference 3

The previous section argued that whether the difference is from 1 to 2 horizons (i.e. a 100% difference in the number of horizons) or from 5 to 6 (i.e. a 20% difference in the number of horizons) had no impact on the strength of the response, a different picture is found for an Euler difference of 3. Here the Euler differences 1 to 2 and 0 to -3 registered a less strong response than for the 'Euler difference 1' experiment. But from -1 to -4 registered a much stronger response.

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[48] At least not to such a degree as would be noticed from this diverse set of images.

One possibility is that the absolute change of Euler Character does affect the strength of response (which would not be inconsistent with the first conclusion) but that the first two images failed to provide sufficiently clear cases. Another possibility would be that the response is not on a linear scale. If the scale is exponential (Figure 41) then moving between E= 1 or -2 and E = -1 or -4 makes a big difference to the response but this would be less apparent for the single horizon difference reported earlier.

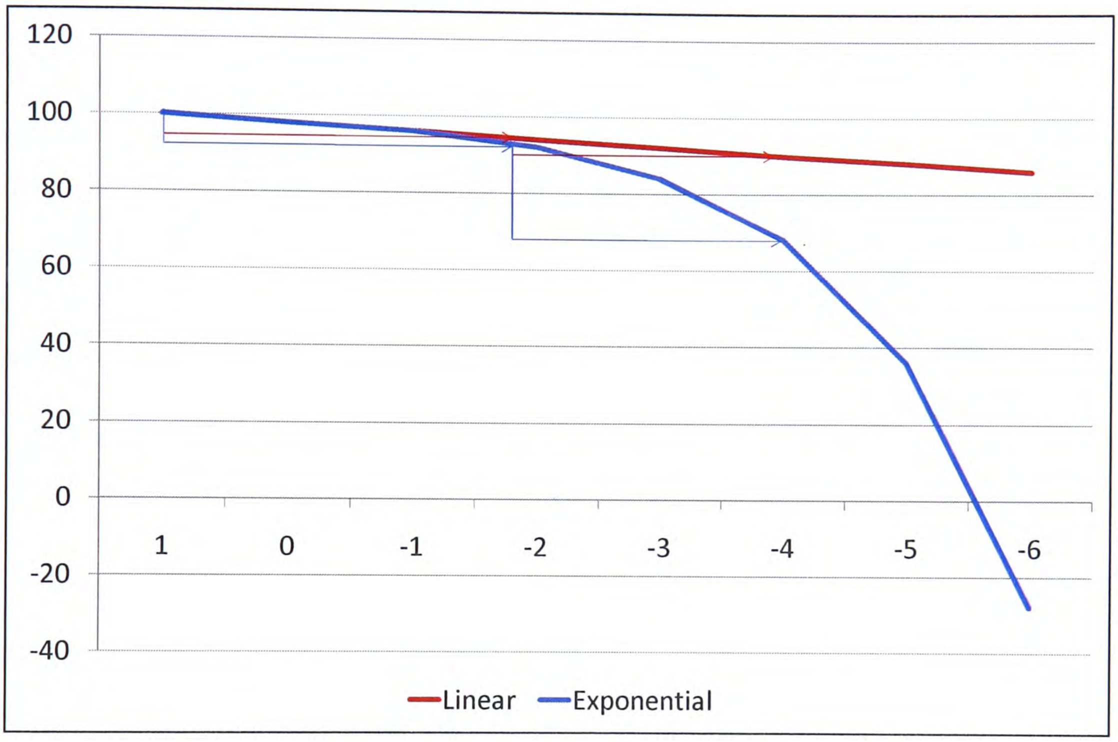

Figure 41 : Effect of an exponential response.

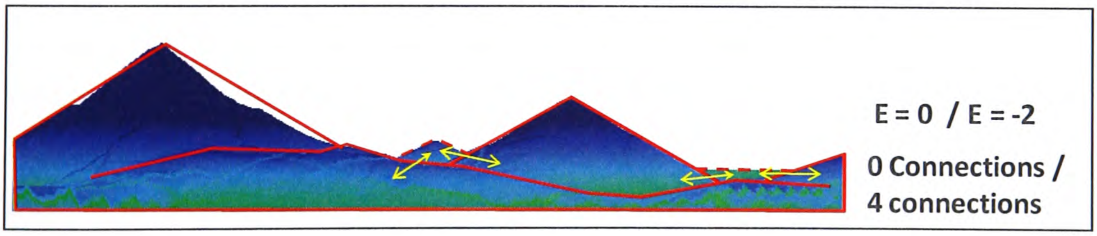

Figure 42 : The Horizon graph, its dual, and the effect of a new edge on the Euler Character.

That the response might be exponential, or at least non-linear, is also suggested by the result for the Roughness experiment, where graph complexity seems to become more important relative to roughness as E decreases. An exponential trend would be mathematically logical in terms of complexity since the connectivity between distinct areas of the view (the dual for the horizon graph (Figure 42)) can, and usually does, increase faster than the Euler number decreases. This means that the number of new horizon edges providing a unique occlusion will increase rapidly, so it would be logical to expect any psychological response to new occlusions to follow that pattern also. This study was intended only to establish if the strength of any relationship between preference and Euler number was stronger for larger differences in E, it was not expected that any indication of a trend would be found from just three points but the difference in pattern does seem to merit further investigation.

The question remains however as to whether the difference measured is really in response to topological complexity, or simply complexity in general? The evidence from the 'Euler Difference 1' experiment suggests a discreet effect which cannot therefore stem from the much more various changes in other dimensions of complexity present in the picture set. But the results from the 'Euler Difference 3' leave some room for doubt on this point. Further differentiation as to the nature of the complexity which may be influencing responses may be sought by considering an additional dimension, roughness.

5.5.2 Roughness difference

Figure 38c shows a range of E values, classified by roughness as either low or high. It seems that despite there being only Boolean values for roughness, the classification was sufficiently consistent to show a clear relationship between the two factors (image pair 10 having been omitted from the analysis for reasons already discussed). Since the data do not continue beyond E = -5, and at E= -5 there is no significant response, one can only say that roughness loses influence as the view gains horizon loops, not that E is the driver of this process. However, given the positive effect of lower E on interest ratings from experiments 1 and 2, it is not an unreasonable suggestion that Euler character increasingly super-cedes or distracts from differences in roughness as it represents more complex topology. Alternatively it may also be that the 'low' and 'high' roughness classifications are less distinct for the lower E-values. Without the full parameter space of Euler number and a quantified 'roughness' it is difficult to be sure which, but the balance of evidence suggests the first theory. Certainly there is a sufficiently strong interaction to merit a specific study of this relationship. In particular, the possibility that the relationship may have an optimal balance between topological and geometric complexity would be consistent with other theories of that suggest medium levels of visual complexity to be the most preferred (Berlyne D 1974; Day 1987).

5.6 Conclusions

The primary conclusion drawn is that topological complexity is related to how interesting a landscape is perceived to be. This is important because it links the literature on topology in human and machine vision with that of landscape preference, and indicates a second dimension to the problem which geometric landscape indicators have thus far not measured. Secondly, these results suggest the Euler number is a cognitively significant measure; however the contagion index (to link with an existing metric) of the horizon graph may be a more direct measure. This needs to be confirmed with a further study.

The contradictory result of image pair 3 suggests cross-horizon contrast to be significant in mediating the role of horizons on perception. While this seems logical, further investigation would be merited.

Finally, there is interaction between topological horizon graph complexity and perception of other forms of complexity. This suggests that topological and geometric complexity may indeed form a parameter space within which perceptions can be modelled. This also requires confirmation through a specific study.

More generally, the fact that horizon topological complexity has relevance to landscape perception supports the arguments in Section 2 that the Euler Zone, dividing as it does an area into discrete units within which an important, perhaps even dominant, character of the landscape is homogeneous, can provide a fundamental mapping unit for landscape character.

6 Section 6 – Discussion, some applications, future work and conclusions

6.1 Introduction

This thesis began with Moran et al.'s (2003) 'great challenge in human ecology' to define appropriate units for analysing human-environment interaction. In particular it was prompted by a recognition that not only were data not available in units relevant for the analysis of the environment as it might be seen by people, but that no suitable definition existed as to what such a unit might be.

In pursuing this line of enquiry it became clear that (to again borrow terminology from Williamson et al. (2003)) before one could develop the product - a visually pertinent environmental dataset - there is much work needed as regards the processes pertaining to that product. These processes might be further explained as two types. One is for an on-going development of suitable data structures to hold, maintain and extract such information, and suitable software to manage this. The other is to add to existing research developing theoretical understanding of human landscape perception, an emphasis on that which might be used to identify distinct landscape units, and to foster its inclusion in landscape planning. In other words, as was argued in Section 1, rather than the development of a single product with spatial units relevant to selected visual, ecological and socio-economic metrics, the aim should be to support a 'process based SDI' e.g. Williamson et al. (2003) and demonstrate the relevance of this to different 'levels of landscape planning' e.g. Marsh (2005).

Section 1 concludes with seven *functions* that such a Visuo-Spatial Data Infrastructure (VSDI) would need to support, in summary:

a) SDI need to ensure support for the *processes* to which data will be subjected
b) Metrics need to be available by individual view point
c) SDI need to provide summary metrics of landscape change
d) Individual level dynamically calculable metrics

e) Metrics are needed to determine how representative viewpoints selected for static presentation are
f) Metrics need to provide information on the robustness of data for a particular view point, including visualised vs. map scale and data heterogeneity within partially visible spatial units
g) An SDI should consider visual analysis use in developing collection units

In order to clarify where in and SDI and Planning context each might make the most contribution however it may help to revisit the SDI pyramid of Rajabifard et al., (Figure 3) and Marsh's (2005) planning hierarchy (Figure 43) :

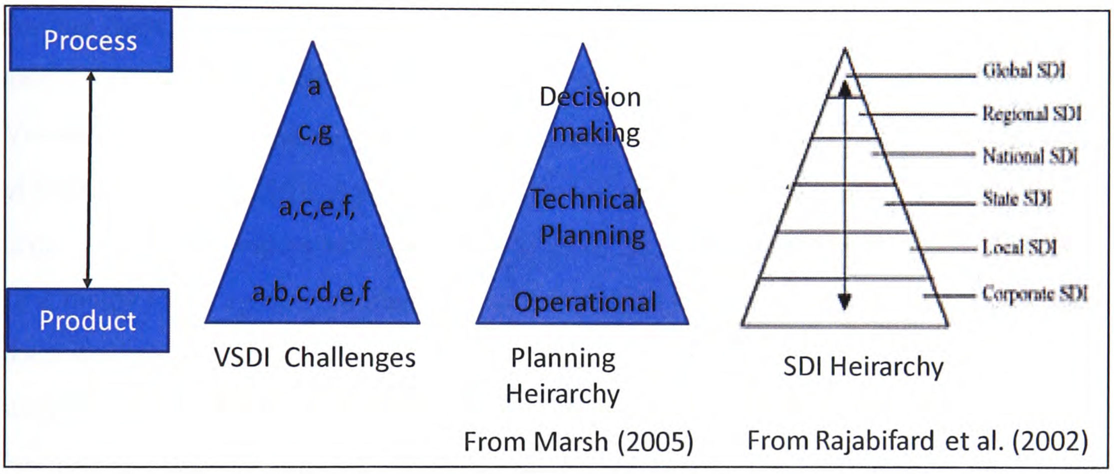

Figure 43 Conclusions of Thesis in relation to EIA SDI functionality and SDI Hierarchy

To consider the research issues that cross the Sections of the thesis, the progress made as regards these functions will be examined in the context of their relationship to SDI and planning:

6.1.1 Decision Making: National to global SDI functions

Function (a) is an over-arching issue at all levels of landscape management, including the product level. The key point here is that as Sang *et al.* (2005) argue, most data producers only consider the processes to which they themselves will put the data or for which they are mandated to produce it. Very few consider the wider possibilities for its use at the product level let alone whether it is conducive to summation for users further up in an SDI. Indeed, the purpose of producing metrics at all (function c) is not generally factored into data production. For example the choice of minimum unit size for land cover classification is not usually influenced by ecologically functional unit size or human visual perception[49]. To include such factors might be considered to inevitably interfere with the 'operational remit' (Sang, Birnie et al. 2005) of the product (i.e. a map) but as one moves from the production of maps to production of landscape models (that is something between raw data and semantically fixed maps) it becomes possible to take into account multiple end uses that might be contradictory to a single cartographic product.

As has been frequently cited in this thesis, assessment of visual landscape character and development of that character (EEC 1985; EC 1997; Daniel 2001; SNH 2004; Vanderhaegen and Muro 2005) is an increasingly likely end use, including via visualization (Bell 2001; Appleton, Lovett et al. 2002; Appleton and Lovett 2005). In order for data providers to the product level to be able to take this into account there first needs to be agreed standards as to the visual characteristics of interest and what their statistical base should be so as to provide confidence that the additional effort would find a ready market. A ready market is likely to be found for some visual landscape information, for example in locations where landscape is a significant contributor to house price (Damigos and Anyfantisa 2011). The ELC mandates landscape be protected "everywhere: in urban areas and in the countryside, in degraded areas as well as in areas of high quality, in areas recognised as being of outstanding beauty as well as everyday areas" (Council of Europe 2000 preamble). As such, function (g) needs to be addressed as a process at the top of the SDI hierarchy and (since landscape does not often recognise international borders) at a supra-national scale.

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[49] The 3Q landscape monitoring scheme being something of an exception Dramstad, W., G. Fry, et al. (2001). "Integrating landscape-based values, Norwegian monitoring of agricultural landscapes, *Landscape and Urban Planning*, 57, 3-4, pp 257-268.".. Aalders *et al.* Aalders, I. H., A. Ode, et al. (2008). "Fixed or flexible land cover classification for the analysis of landscape functionality? *In Proceedings IP SENSOR Conference: Impact Assessment of Land Use Change - Multifunctional Land Use*, Humboldt University, Berlin, Germany, 6-9 April 2008.". propose flexible classifications of land cover according to purpose, including visual analysis.

It is believed that one contribution of this thesis is to have made the call, in Section1, to begin the process of agreeing what visual characteristics of a location should be taken into account when monitoring land cover and suggest a possible spatial base for this in the Euler Zone.

6.1.2 Technical Planning / State (county) to national SDI functions

Summary metrics (again function (c)) can also be of use at the technical planning level, for example to monitor cumulative visual impacts (SNH 2004). Although summaries may be aggregated from individual viewpoints, and might be used as qualitative examples in technical planning, function (b) is excluded here as being more likely to be of use locally for specific planning applications. When individual views are used, or summarised, at the technical level it is important to identify representative viewpoints (function (e)), to ensure that the summary metrics are representative. Information about the robustness of the underlying data used to analyse each point, function (f), is also required to ensure cumulative error is not significant in the aggregated statistics.

Functions (e) and (f) in particular prompted the search for a landscape metric that might be locally stable to viewpoint change so as to provide a set of discrete spatial base units. In Section 2 it was argued that most scene metrics must vary in some parametric way with viewpoint change, since the effect of perspective on length and area is itself a mathematically tractable process. The exception to this is when objects appear or disappear due to occlusion. It was recognised that since horizons are, by definition, the 'objects' mediating occlusion, they must also mediate the non-parametric component of variance in scene properties due to viewpoint. If one knew where on the map such horizons and their shadows fell, one could at least detect when non-parametric change occurs and perhaps even predict some of its effects.

This recognition lead to the idea of modelling the relationship between land forming a horizon and that visible beyond as a topological link which is perhaps the central contribution of this thesis. Whilst many potential implementations of visibility analyses can be developed, the Horizon-Shadow link opens up possible solutions to all of the SDI functions listed above, as well as other interesting applications discussed below. In particular, the link between the data and the visual metrics is much stronger because metrics based on *perspective* analysis can be summarised spatially (function (c)) and aggregated to higher levels of abstraction. The links explicitly connect shadows to the spatial units they occlude, providing the means to detect MAUP (one aspect of robustness in summary statistics, function (f).

The other aspect of topology introduced in this thesis has been the idea of graph complexity of horizons. It is worth emphasising that, despite the common terminology, this is a quite separate issue from that of how to manage the topological links between foreground and background[50]. The horizon graph is probably of most use as input to metrics of scenic quality, since it captures aspects of variance in depth of view, found to be correlated to scenic beauty (Bishop, Wherrett et al. 2000) particularly with the dramatic effect of mountainous landscapes. Certainly the metric of Euler Character seemed to show association with how 'interesting' a landscape was, though more investigation is needed as to why.

As such the idea of the horizon-graph, graph metrics in general and the Euler Character in particular might be of most use at the Technical Planning level by adding perspective based metrics to assess the effect of development on areas that form, or have a view onto, rolling or mountainous scenery. Since by definition, horizons do not exist in orthographic view this would only be available by deriving it on a case-by-case basis, or by embedding the information into a data structure as has been done here. But the Euler Character of the view around a location could, at least, be supplied as a pre-calculated map.

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[50]Without these links building the graph would not be possible but the utility of the latter is as a general data structure for line of sight relationships, not simply as a means to construct the horizon-graph.

6.1.3 *Operational Planning*

Operationally, the need to objectively measure change (a derivative of function c) is arguably less in need of automation, indeed some argue that the process is fundamentally qualitative (Gaber 1993). But the case for automation to detect when significant change occurs (which of course entails some quantitative definition of significance) is harder to dispute. Detecting significant landscape change (function d), i.e. change likely to be a source of dispute, entails being concerned with particular viewpoints (function b). Aside from the sheer volume of possible considerations for all the individual proposals each year, there is also the question of what time period to consider. Cumulative visual impacts along one line of view can be very significant. For example in the case of wind turbine development, concerns are raised both as regards the aesthetic impact (SNH 2004) and because of the relative movement of turbine blades, and the flickering of sunlight through them (referred to as 'shadow flicker'), which may trigger stress or even epileptic fits (Harding, Harding et al. 2008). This is a line-of-sight specific problem and therefore difficult to manually predict from a plan. To avoid such problems, planning currently relies on the local knowledge of planning officers, which may be in decline if as the Town and Country Planning Association claim, high staff turnover at all levels of the system are already a cause of delays in decision making (TCPA 2010 p.3). Furthermore, avoiding cumulative visual effects also requires co-ordinated knowledge of pending plans, including those in other planning authorities.

Figure 44: A 'view' of a chimney framed by an avenue in Pildams Park, Malmo, Sweden.

Other effects may be more subtle but not less significant. For example the prominence provided of a tall structure such as a turbine or chimney as viewed from one particular angle, as in Figure 44, due to the 'frame' of the terrain (Bell 1998) unless that particular location is visited at the right time of day and year (Miller and Morrice 1995). It would also, therefore, be hard to establish who might be directly affected by such an unfortunate congruence of circumstances. Section 3 has set out how the data structure developed can render such problems more tractable to computation and open the possibility for automated change detection and warning, potentially on a per-household basis. This could help to substantially reduce the problem of information overload due to the complex evidence base now required (TCPA 2010 p.3) by allowing threshold filters to be developed based on the current legislation and focusing detailed expert consideration in such cases on the most vulnerable lines of sight. The other aspect of dynamic landscape metrics – where it is the point of view changing rather than the landscape itself – is also potentially important. The issue of flicker for example may be generated by changing occlusions as angle of view changes at speed, as when driving, or more positively a rapidly changing view may be a source of interest to be highlighted for tourists. This is of particular importance in the assessment of cumulative visual impacts of features, such as wind turbines. In this thesis a start has been made to consider how development of data structures might open new options for modelling dynamic views, which set out in principle in Section 3 and in detail in Section 4. 'Walking' a horizon rather than re-scanning it seems to offer considerable potential for improvements in real time modelling, although the implementation set out in Section 4 may only be relevant in very limited circumstances, road navigation being one example.

At the operational level, using metrics to determine the most representative view points (function e) is relevant to ensuring that material presented for public consultation is a fair representation of the proposed changes. It is also a topic that could benefit from automation since it is impossible to visit all the potential viewpoints, and even if one could do so selecting representative viewpoints qualitatively would be problematic. Section 2 argues that the nature of topological change means that discrete areas could demarcated between locations where the topology of the view changes. Given the earlier point as regards the role of horizons in mediating occlusion, this should that mean all potentially visible land covers in the area would be visible from at least one such unit. However, while existing definitions of what constitutes the topology of a view onto an object exist (e.g. the aspect graph (Plantinga and Dyer 1990)), these are likely to produce many small spatial units in a landscape context. The Euler Zone represents a subset of those based on the Euler Complexity, but as such could only be objectively justified if Euler Complexity is psychologically salient. The experimental results in Section 5 suggest that is the case and thus points within each Euler Zone would be a useful starting set.

At least in the sample of images from which the survey test set were selected, the range of Euler Characters to be found in a view was limited, from 1 (at the simplest) to -6 or -7 at the most complex. So if Euler Zones were also too numerous, one could select a stratified-random sample of these (stratified by Euler Character) and be confident that all large scale (i.e. landform) circumstances were covered. If Sang et al. (2008) are correct in the suggestion that the correlation between perception of landscape and some landscape metrics is robust to some change in perspective then this need not reduce the representativeness of the view-set significantly. Indeed if, as Dramstad et al. (2006) suggest, people are able to predict some features such as water even when these are hidden from view then it may be that considerable leeway exists in view point selection. None-the-less it is probably commonly understood that significant occlusion can bias the impression of an area, and a views topology could serve as an objective minimum guide.

Qualitative judgment as to what information to include in a planning consultation is ideally made by people with some expertise relevant to the task. However, where such material includes computer generated images from multiple supposedly objective, data sources, it is unlikely that anyone will have sufficient expertise in all areas to remove the risk of significant errors, as the data is being used for tasks beyond that for which it was intended. Unlike the Decision Level in planning, whereby the errors would need to be consistent and widespread in order to affect net statistics, at the operational level the effect of misclassification of a part of the view (due to its being part of a larger map unit) can be literally magnified by the presentation method, thus foreground could be rendered as pasture when it might be have been more correctly classified as rough grassland had the surveyor chosen to draw the boundary a few meters away. Thus at the operational level function (f) is very important and horizon and shadow lines now provide a mechanism by which that particular aspect of accuracy may be tested on a per-view basis.

6.2 Implementation of functions

Having set out the potential contribution to each level of the planning system it is important to recognise that, in pragmatic terms, the adoption of most of these methods will depend on software which can handle the suggested data structure and run the necessary algorithms to generate the horizon-shadow links, as well as build and analyse the horizon graph. Moreover it would need to do so via robust, easily operated software that can be integrated into existing planning systems.

It is acknowledged that the implementation presented requires further development before it could be deployed. Section 4 details some of the specific technical improvements needed, such as an improved perspective engine and integration into a mainstream GIS. However, important lessons have also been learned as to how to achieve such an implementation:

- Robust Computation is essential: Small rounding effects from the use of floating point calculations occurred throughout the development process and considerable time was spent distinguishing the effect of this from problems with the algorithms themselves.
- Provide for Multi-Edge Occlusions: Whilst the belief that distant TIN edges are unlikely to be occluded by more than one horizon edge remains reasonable, it is not so rare as to be completely discounted. This situation may occur with low resolution datasets of highly variable terrain. Even if not anticipated to be a problem in application, it will make development smoother and the same facility may be of value in maintaining multiple viewsheds simultaneously. The algorithm for HSR and Horizon shadow linking is also less straightforward than might be assumed and is worth consulting for future implementations.
- Use Pointers for Horizon-Shadow Topology: the use of pointers to manage horizon-shadow links has exceeded expectations as to its simplicity and efficiency. However the decision to record only Shadow-Horizon links and not vice-versa considerably complicated reading the mGraph, for a relatively small efficiency saving.
- Keep the Euler Calculation Simple: when calculating the Euler Character, it is only necessary to count the number of graph edges and nodes, not achieve a continuous graph traversal.

The limitations identified in Section 4 are significant but do not cast doubt on the potential utility of the methods set out in Section 3. The final map obtained is far more efficient in terms of space, and richer in terms of the amount of information which can be extracted about the view.

6.3 Further potential applications

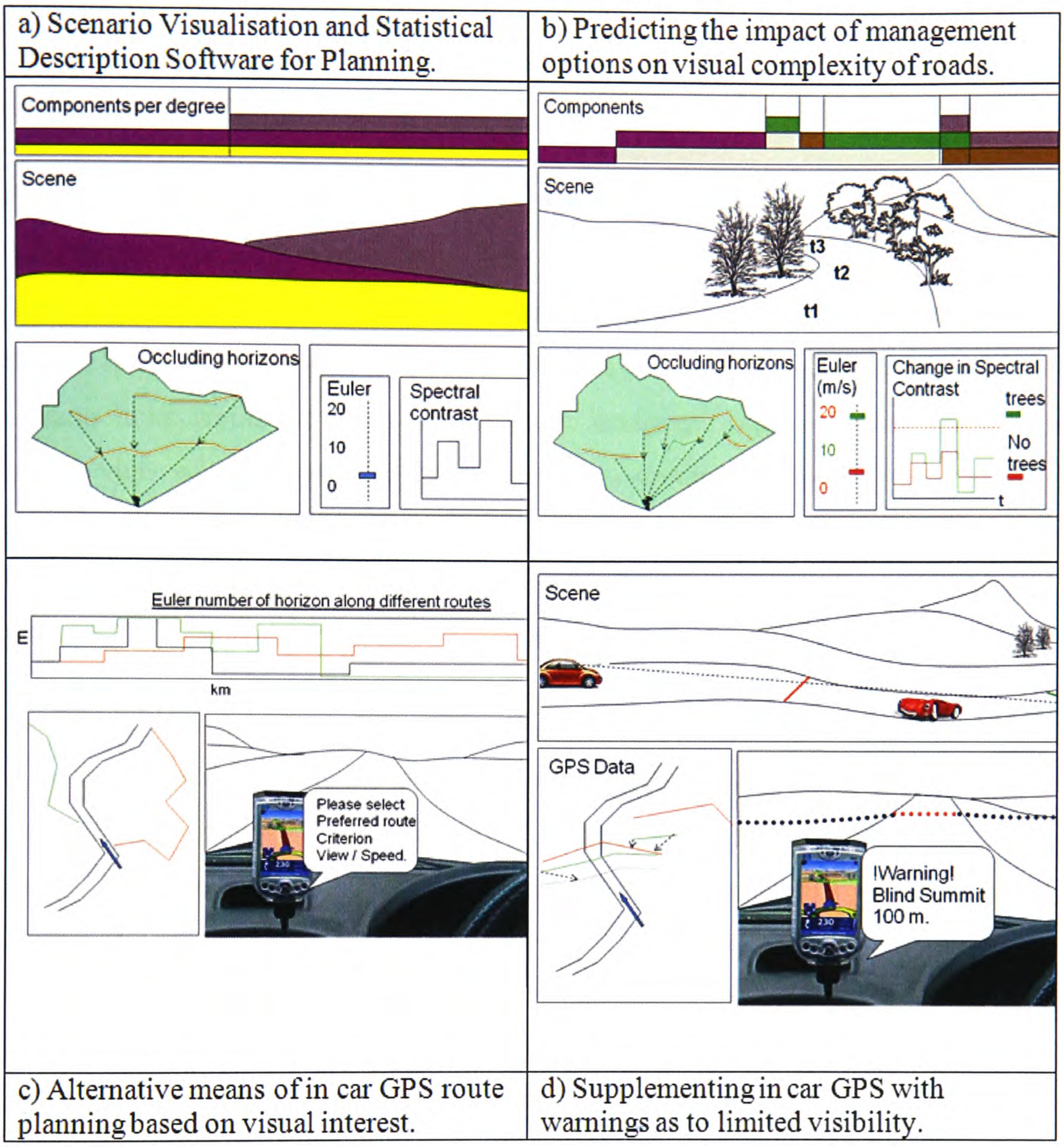

Figure 45: Illustrated applications

Topological mapping of visibility represents a viable and fundamentally new way of thinking about and undertaking visual analysis in GIS that could be of use in a wide variety of applications beyond planning and modelling landscape preference.

The most obvious application would be a general landscape management tool (Figure 45a). This could provide statistics on landscape character for particular viewpoints and view angles based on the map data, providing summary data as to what is visible, where on the map this is and providing landscape metrics for the view and map data for comparison. These could be either displayed to a user, for example a planning officer looking for places from which to view a potential development site. Alternatively, the information could be analysed automatically to provide summary reports or via multivariate optimization (Sang 2010) to suggest representative viewpoints.

Figure 45b illustrates how such a system might be of use in landscape management along roads. Visual topology could help identify where the large scale changes in scene occur along a route and then help monitor these (as per Figure 36b) for changes in cross horizon contrasts or depth of view. The visual field represented by Shadow-Horizon links would be intersected by any landscape changes which occlude the drivers view of the road (e.g. trees reaching a certain height), so these could be automatically detected and a warning issued. Similarly stark cross horizon contrasts might be considered distracting and merit screening off to ensure concentration on the road.

Speed may also be factored in when considering likely interest. For example, the lower the Euler Character, the more occluding horizons there are, and the more these intersect each other. Viewed when moving, this produces relative motion between horizons as ground is occluded or revealed. Theoretical concepts such as landscape mystery (Kaplan and Kaplan 1989) explain why a landscape which constantly reveals new things will hold one's interest more than one which changes only gradually. Thus, as Figure 45c illustrates, the Euler Character could be used with in car GPS to predict more interesting routes, rather than just the quickest route.

Figure 45d shows how the system might work with in car GPS to monitor the road ahead for hidden dips in order to warn against overtaking. By identifying the visual field from a horizon to its shadow, when the most distant surface is also classified as road it is likely that the contrast will be low and the driver may be unaware of the dip. The maximum depth of the visual field may also be estimated to establish if a vehicle could be entirely hidden from view. It is believed that in-car navigation is one area where dynamically 'walking' horizons and their shadows could play a valuable part.

Also relating to navigation but in a different context the ability to analyse scenic landform could be used to populate near shore marine navigational aids with likely notable landforms. This would entail additional work on what geometry is notable (Mark and Turk 2003)[51], but using landmarks based on notable abstract horizons is a long established tool in these circumstances; Porathe (2007) cites the practice as far back as the 16thC.

6.4 Conclusions

6.4.1 Advantages of a topological data structure for modelling visual landscape perception

a) The topological model

This thesis has set out a method for handling visual landscape perception which is, as far as the author is aware, based on a new conceptualization of the problem: that the spatial arrangement in perspective view constitutes a set of topological relationships in orthographic view or, to phrase it concisely, that the Visual field (Cova and Goodchild 2002) has its own topology[52]. This topology allows the scene to be navigated computationally via the map which has several advantages over traditional methods of viewshed analysis of the map, and image analysis of the scene:

- The viewshed and scene topology are maintained as a single integrated dataset, thus properties unique to one or the other can be accessed

[51]Hirtle and MacEachren Hirtle, S. and A. MacEachren (1998). "Cognitive Models of Dynamic Geographic Phenomena and Their Representations, *Varenius Workshop Report*, Pittsburgh, PA, October 28-31, 1998.". presents the results of an interdisciplinary workshop on cognitive modelling of geographic space, including issues of landmarks and navigation. The range of disciplines, from psychology to geography, computer science and art indicates the nature and complexity of the task.

[52]While O'Sullivan, D. and A. Turner (2001). "Visibility graphs and landscape visibility analysis. *International Journal of Geographical Information Science*, 15, pp 221–237.". do recognize inter-visibility between points to be topological they do not connect this with topological links between occluding and occluded area.

simultaneously. For example, spatial context is only available from the map, while apparent landscape morphology is only available in the scene.

- Scenic properties, such as visual framing (Bell 1998) can be analysed directly while still drawing on attribute information from the map.
- Scene statistics remain directly connected to their location in the map, so do not need to be derived from the image and re-assigned to the map (removing one source of potential errors).
- Visible landscape change can be automatically detected, and updated in the scene.
- Viewpoint dynamics *may* be made more efficient by 'walking' horizons and their shadows since the new viewshed is likely to fall near to the previous viewshed.
- Issues of MAUP due to perspective projection and occlusion can be detected.

Given the above advantages it would seem reasonable to conclude that overall, the introduction of visual topology would significantly strengthen the links between visualization and the spatial data on which it is based, providing explicitly traceable foundations to visualisations and a qualitatively richer analytical capability.

b) The data-structure

That the data-structure can be implemented as pointers within a Delaunay TIN has several additional advantages. The use of the Delaunay-Voronoi TIN model itself has a number of advantages for terrain modelling. These cannot be put better than has already been elucidated by Ledoux[53] :

"1. The [Voronoi Diagram] offers a natural discretisation of space, which is based on the samples that were collected to study the field. The phenomena studied can thus be represented freely, and not enforced by a rigid structure like voxels. The shape and the size of the cells in the VD are adaptive to the spatial distribution of the samples, which is crucial when dealing with highly anisotropic distributions such as the ones found in the geosciences.

2. The one-to-one mapping between the points and the Voronoi cells ensure that the original samples—the meta-field according to (Kemp and Vckovski 1998)—are kept and not 'lost', as is the case when gridding."

(Ledoux 2006 p.147)

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[53]Ledoux, H. (2006). "Modelling Three-dimensional Fields in Geoscience with the Voronoi Diagram and its Dual, PhD Thesis, University of Glamorgan, November 2006.". lists a further five advantages of the Voronoi-Delaunay structure, which are not set out in detail here as that is not the central issue of this thesis but are nonetheless useful.

That fact that the structure is topological and can support an object-segmentation based HSR method, means that it not only works well with TIN (ray tracing, for example, becomes complicated due to the variable cell size), but can actually use the same basic structure of pointers, making it a natural addition to triangulated Digital Terrain Models[54]. Using a system of pointers to represent the topology (which could of course also be implemented as pointers between raster cells) has additional advantages:

- Visual Topology pointers can hold the visual field within the DEM allowing viewshed geometry to be re-constructed without further perspective calculations.
- VT vectors also reference as their end nodes objects in the landscape rather than just co-ordinates. If one of those objects is moved, the new vector is automatically adjusted so the 'minimum visual hull' need not be maintained as a separate geometry, only checked for continued relevance.
- Embedding the visibility model in the DEM is very efficient compared with raster viewsheds (which must record every cell's visibility, and so are usually the same size as the original data[55]. Indeed, it is interesting to note that a viewshed 'map' modelled by the data-structure proposed does not require more memory with higher resolution terrain.
- Embedding the visibility model into the DEM also retains the spatial context of the visibility map, a key problem with previous topological models such as O'Sullivan and Turner's (2001) visibility matrix.
- Multiple viewsheds could be held simultaneously within the same dataset simply by replacing a TIN edge's shadow-horizon link attribute with a list.

6.4.2 Advantages of topological metrics for determining the spatial statistical base of a landscape SDI

The case for a common spatial base being necessary in order to analyse spatial socio-environmental problems has been made exhaustively, both in this thesis and by others (Openshaw 1984. ; Moran, Siqueira et al. 2003). The ability to define spatial units

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[54] Digital Terrain Model is used here as the triangulation method of presenting a Digital Elevation Model involves a particular interpolation method for the terrain.

[55] Compression techniques such as Run Length Encoding and Quad-trees Laurini, R. and D. Thompson (1999). "*Fundamentals of Spatial Information Systems*, Academic Press, London.". can reduce the memory size but must be decompressed for processing

relevant to landscape perception however, requires salient visual characteristics that would be sufficiently constant over space to define a 'homogeneous' zone. In identifying that the topological characteristics of a landscape are perceptually salient and locally stable, an important Rubicon has been crossed. Establishing that not all aspects of visual landscape perception continuously change with viewpoint raises the possibility of discrete spatial units where in at least one visual characteristic is homogenous.

The question is then raised however, as to what topological measures might be stable over sufficiently large areas, and are these salient to landscape perception? It is reasonable to suppose that there will be some optimum front to this problem since, as a measure becomes more stable over space, so that space will also encompass a greater variety of land covers. Thus it remains to be established whether the Euler Zone suggested here will indeed present a suitable landscape unit to which to attach a host of other information. However several characteristics recommend it:

- The perceptual salience of Horizon-Graph complexity as measured by Euler Character
- A sound foundation in mathematics as a descriptor of shape.
- Homeomorphism (thus many different topological graph arrangements may produce the same Character value. This makes it more likely to produce larger spatial units)
- Horizons mediate many elements of landscape character, e.g. depth of view, spatially separate landscape patches, cross-horizon contrasts and horizon geometric elements
- That topological complexity correlates, regardless of the land cover context, with how interesting survey respondents found a landscape to be, suggests it to be a useful metric in itself, rather than simply mediating metrics such as diversity and richness

Having extolled the advantages of one particular option, the discussion in Section 1 showed that a process based SDI is more likely to succeed, rather than a single 'product' whereby a spatial unit is determined to which other information must conform. By a process model, multiple different definitions of visual landscape units may begin to be generated by different actors. Some will take advantage of the stationarity of topological metrics recommended here; others may prefer some variance minimizing classification. Perhaps the greatest challenge from an SDI perspective will be to raise the profile for visual factors as a significant issue at the point of data collection, and counter the presumption that such is impossible because it's 'a matter of perspective'.

6.5 Summary of contributions to academic fields

As stated in the Introduction, this thesis has operated at the nexus of several academic fields. Contributions have been made to different fields, which are identified below, many of which stem from cross-fertilisation of existing ideas between fields – the use of Euler Character as a shape descriptor being an obvious example. The thesis builds upon the ideas and methods of others, in particular Gold et al. (1996), De Floriani et al.(1996), O'Sullivan and Turner (2001) and Cova and Goodchild (2002), the topological mapping of horizons to the shadows they cast is, as far as the author is aware, a fundamentally new way of thinking about visual analysis, and of mapping a viewshed in GIS.

Landscape Research

- The introduction of visual topology as a dimension of landscape character
- The recognition that landscape metrics based upon topology will generate discrete homogenous map units
- The conceptualization of horizons in a view as a graph
- Highlighting that MAUP may be an issue in landscape visualization and that this should be considered during data collection
- Development of data-structures and algorithms specifically to address the limitations of existing GIS for landscape research, in particular the current disconnect between planar and perspective statistics
- Demonstrating the perceptual salience of Horizon-Graph complexity as measured by Euler Character

Spatial Data Infrastructures

- The recognition that landscape metrics based upon topology will generate discreet homogenous map units. In particular the use of apparent topological relationships across horizons. Since these mediate many elements of landscape

character, the ability to discretise space by apparent horizon characteristics could bring visual aspect of landscape management within the scope of INSPIRE.
- The argument that SDIs such as INSPIRE must consider visual analysis in general and visualization in particular as an important end use to which data is likely to be put at all levels of landscape management.

GI Science / Computer Science

- Embedding Shadow-Horizon links into the TIN as pointers is a significant improvement in efficiency for storage and update of viewsheds
- Walking the horizons is not fully demonstrated as a generally viable method, but it has been demonstrated as possible in limited circumstances and, if the range of circumstances can be widened it should provide an elegant and efficient solution to dynamic view change
- A number of useful lessons in how to implement software for visual-topology management

The overall value of the concept of Visual Topology as set out in this thesis might be assessed by whether these contributions disprove the three null hypotheses presented in the Introduction :

Null 1 – No spatial base unit exists that can be objectively defined by a visual landscape metric and is stable under local view-point change. – *Disproven (Section 2.4-2.6; Section 5.2.2 ; Section 5.4).*

Null 2 - Apparent topological complexity is not associated with viewer perceptions of landscape. – *Strong evidence against (Section 5.4-5.6)*

Null 3 - Visual Topology does not: (a) Reduce storage requirements for results of visibility analysis compared to a traditional raster viewshed –*Disproven (Sections 4.14-4.15.2)*; (b) Allow faster query of a changing view than existing standard GIS methods - *Disproven as regards landcover attribute change (Section 4.15.2), and more work to be done as regards viewpoint change (Section 4.17)*; (c) Allow information about a view (in terms of its geometry and topology) to be queried directly from Digital Terrain Data beyond that available by standard GIS methods – *Disproven (Sections 3.9 and 4.18-4.19).*

As to the convergence of these elements in a single landscape map product perhaps, given the observations of Rajabifard and colleages (Rajabifard, Feeney et al. 2002; Williamson, Rajabifard et al. 2003; Rajabifard 2003, ; Williamson, Rajabifard et al. 2006; Rajabifard 2007) as to how co-operation is successfully achieved in SDI, one might rephrase Moran et al.'s (2003) challenge as being to: 'facilitate a process which enables landscape data collection to reflect the ephemeral and perspectival nature of human experience.'

6.6 Further work

The work in this thesis has served to open up the visual landscape to more computational analysis. In addition to the further software improvements already suggested to be as necessary to take VoronoiMagic LITE beyond a prototype functionality, it presents several research questions for future work:

a) What other locally invariant landscape metrics can be defined?
b) Given Hagerhall et al.'s (2004) observations on scale and perception; Can a hierarchy of topological metrics be defined, such that each identifies the sources of discreet variance in landscape character at a given perceptual scale or range of fractal dimension?
c) How can a data-structure best encode the manner of change in visual topology that may be due to climatic circumstances, presentation medium, visual acuity and even attention (University of Newcastle 2002; Ogburn 2006).
d) How can the variance of other metrics within discreet topological units be measured, and norms identified?
e) Tarr and Kriegman (2001) present an interesting set of results to the effect that some forms of topological change seem to be more salient than others, and it is noteable that these higher salience events are those where graph loops are added or removed. It would be interesting to establish whether their results can be replicated with landscape stimuli.
f) From an organizational point of view, how can an SDI process be developed that presents data collection agencies with a persuasive case for considering the visual landscape when defining land cover classes and determining map unit boundaries?
g) Can the 'horizon walking' algorithm be sufficiently generalized to allow rotation of viewpoints or 'reversing' along the line of sight? This would entail the introduction of unprocessed areas of the map, preferably without resorting to a new global visibility analysis.

Two larger prizes for future research are also identified:

1) In the modelling of visibility a problem was noted that pointers currently run from the shadowed edge toward the viewpoint. However, this counter-intuitive model of visibility may prove useful. If each TIN edge is considered to form the diameter of a sphere, then each of these vectors will form a point on that sphere marking an angle of occlusion. The occlusion will, theoretically, remain the case regardless of the proximity of the viewer, being determined only by the viewing angle. When that view point moves, this relationship may be rechecked (as per the 'walking' algorithm) and if still the case then an angular vector has been found along which the occlusion relationship holds. If the relationship changes, to either a different shadow-horizon pair or to the previously shadowed edge becoming visible, then at some point along that vector the relationship must be held to have changed. Precisely where this might be is unknown, but a point equidistant could be reasonably presumed to minimize the potential error to its true location. As more viewpoints are added, these estimated points of change may be linked together, to form a dual of the vectors – i.e. the Voronoi area over which one or other visual relationship is more likely to hold than that of its neighbours. The Voronoi diagram (on a spherical view-sphere around the mesh edge) would thus be refined as the landscape is explored. Each sphere would in essence be an aspect-graph (Plantinga and Dyer 1990) for the view outward from, rather than onto, each edge. The resulting network of Visual Topology Spheres would not only encode the visibility map locally as far as it is known, requiring only an object query with the angle of view to determine the VT, but there is also some basis for predicting the VT along an gles to viewpoints that have not yet been visited. The premise seems logical but a great deal of work will be needed to demonstrate it is theoretically correct and computationally feasible.

2) Without suggesting that anything approaching the refinement of their model has yet been achieved, it is hoped the ability to handle topological and spatial order queries (Egenhoffer 1989) in perspective that has been developed here could lead to an equivalent model for perspective relations as Egenhoffer and Herring's '9 Intersection' (Egenhoffer and Herring 1990) model for planar spatial problems.

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7 Appendices

7.1 Appendix 1 – Psuedo code (See CD Rom)

7.2 Appendix 2 – Code extracts (See CD Rom)

7.3 Appendix 3 – Results of tests of VoronoiMagic LITE

Table 3 Results of Tests of VoronoiMagic LITE

Test	Data Set	Nodes	Nodes Height > 0	View coord X	View coord Y	Shadow-Horizon Links	Spatial Graphs	Horizon Graphs	Euler number(s)	Pass/Fail
1	Set1	603	41	-9,8	1,2	1	2	1	4	Pass
2	Set1	603	41	0,2	8,7	3	3	1	0	Pass
3	Set1	603	41	9,8	9,8	2	3	1	1	Pass
4	Set1	603	41	9,8	3,4	2	2	1	0	Pass
5	Set2	465	62	-9,8	3,4	2	2	2	0;1	Pass
6	Set 2	465	62	-9,8	-9,8	4	2	1	-1	Pass
7	Set 2	465	62	0,2	9,8	4	2	1	-1	Pass
8	Set2	465	62	9,8	9,8	4	2	1	-1	Pass
9	Set 2	465	62	9,8	3,4	4	2	1	-1	Pass
10	Set 3	455	28	-9,8	3,4	7	2	1	-3	Pass
11	Set 3	455	27	-9,8	9,8	6	2	1	-2	Pass
12	Set 3	455	27	0,2	9,8	6	2	1	-2	Pass
13	Set 3	455	27	9,8	9,8	6	2	1	-2	Pass
14	Set 3	455	27	9,8	3,4	4	2	1	-1	??
15	Set 4	453	54	-9,8	3,4	14	7	1	-3	Pass
16	Set 4	453	54	-9,8	9,8	14	7	1	-3	Pass
17	Set 4	453	54	0,2	9,8	14	7	1	-3	Pass
18	Set 4	453	54	9,8	9,8	9	6	1	-4	Pass[56]
19	Set 4	453	54	9,8	3,4	9	5	1	-4	Pass
20	Set 5	453	60	-8,7	3,4	13	8	1	-6	??
21	Set 5	453	60	-9,8	9,8	13	8	1	-5	Pass
22	Set 5	453	60	0,2	9,8	13	8	1	-5	Pass
23	Set 5	453	60	9,8	9,8	14	8	1	-7	Pass
24	Set 5	453	60	8,7	3,4	13	8	1	-6	??
25	Set 6	132	8	0,2	9,8	6	7	2	1,0	Pass
26	Set 6	132	8	9,8	9,8	5	5	2	-1;1;	Pass
27	Set 6	132	8	9,8	0,2	6	7	2	0;1	Pass
28	Set 6	132	8	9,8	-3,4	7	7	2	-1;1	Pass

[56] Tests 18 and 19 record an additional horizon shadow link because the viewpoints are sufficiently oblique to the ridges that two parallel lines meet at a vanishing point. However this is due to the resolution of the calculation. This is classed as a pass here as it is the correct decision within the limits of the resolution.

29	Set 6	132	8	9,8	-9,8	5	5	1	0	Pass
30	Set 6	132	8	2,1	-9,8	7	5	3	1;1;-1	Pass
31	Set 6	132	8	-9,8	-9,8	4	4	2	1;0	Pass
32	Set 6	132	8	-9,8	0,1	2	4	2	1;1	Pass
33	Set 6	132	8	9,8	9,8	8	7	1	-1	Pass
34	Set 7	134	11	0,2	9,8	5	6	1	0	Pass
35	Set 7	134	11	9,8	9,8	6	6	2	-1,1	Pass
36	Set 7	134	11	9,8	0,2	6	6	2	0,1	Pass
37	Set 7	134	11	9,8	-9,8	7	6	1	0	Pass
38	Set 7	134	11	0,9	-9,8	7	8	2	1;1	Pass
39	Set 7	134	11	-9,8	-9,8	5	6	2	0,1	Pass
40	Set 7	134	11	-9,8	0,2	2	4	2	1;1	Pass
41	Set 7	134	11	-9,8	9,8	10	8	1	-1	Pass
42	Set 8	595	144	0,2	9,8	16	14	1	-4	Pass
43	Set 8	595	144	9,8	9,8	20	14	1	-8	Pass
44	Set 8	595	144	9,8	0,2	17	11	1	-5	Pass
45	Set 8	595	144	9,8	-9,8	47	14	1	-24	??
46	Set 8	595	144	0,2	9,8	16	8	1	-31	??
47	Set 8	595	144	-9,8	-9,8	46	12	2	-21;1	??
48	Set 8	595	144	-9,8	0,2	12	6	1	-5	Pass
49	Set 8	595	144	-9,8	9,8	14	8	1	-9	??
50	Set 9	412	116	8,8	-9,8	4	4	1	1	Pass
51	Set 9	412	116	0,2	-9,8	3	5	2	0;1;1	Pass
52	Set 9	412	116	-9,8	-9,8	6	7	2	0;1	Pass
53	Set 10	441	106	-9,8	3,1	17	15	1	-6	Pass
54	Set 10	441	106	-9,8	9,8	23	16	2	-5,1	Pass
55	Set 10	441	106	0,2	9,8	24	11	1	NA	*Crashes
56	Set 10	441	106	9,8	9,8	41	13	1	-18	??

?? = Uncertainty as to pass due to complexity of horizon graph.

7.4 Appendix 4 – Images from Landscape Survey

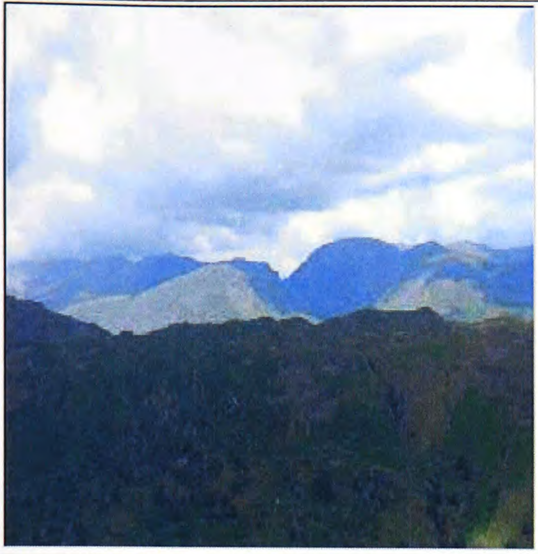
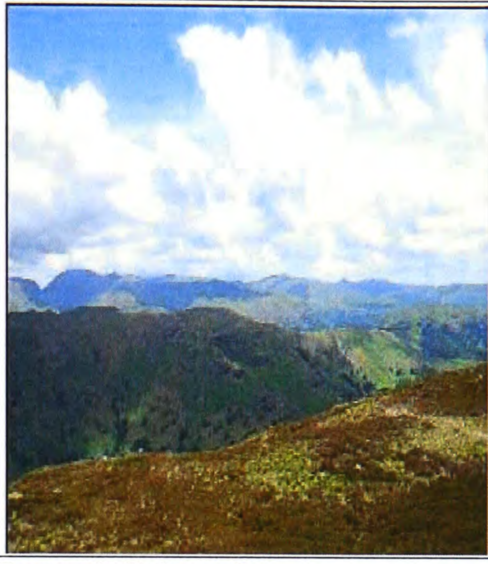
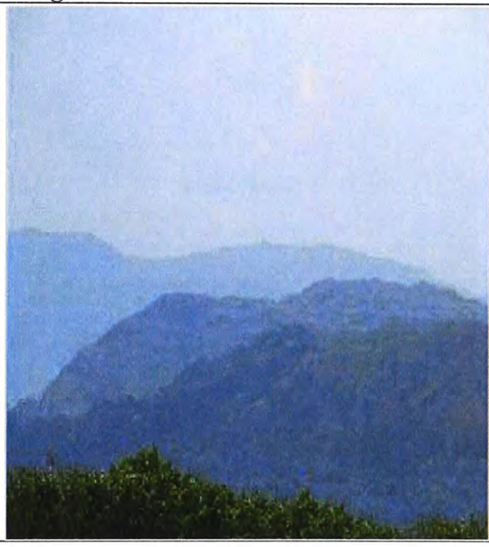
Image 1 : Euler = 0	Image 2 : Euler = -1	
		Pair 1
Image 3 : Euler = -1	Image 4 : Euler = -2	
		Pair 2

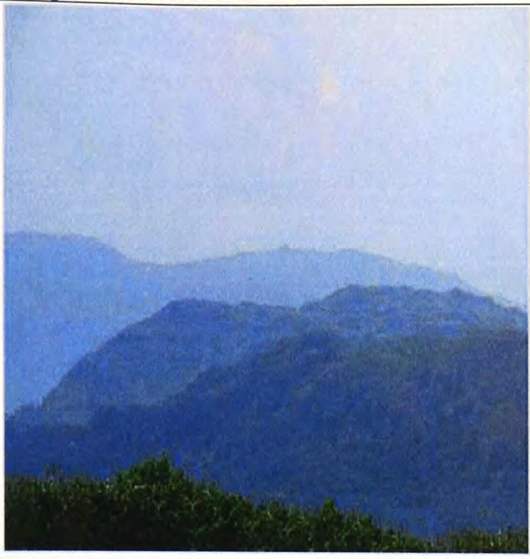
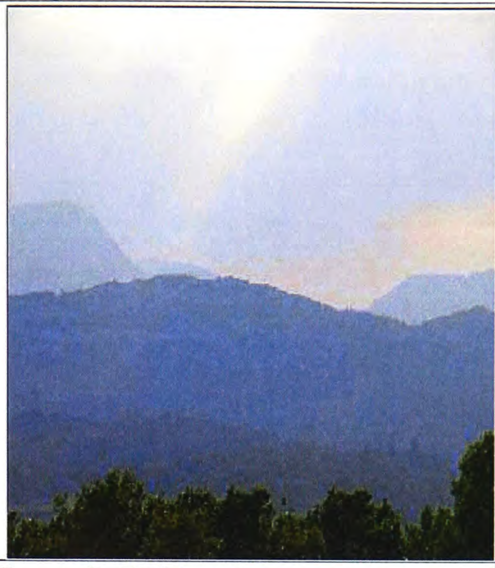
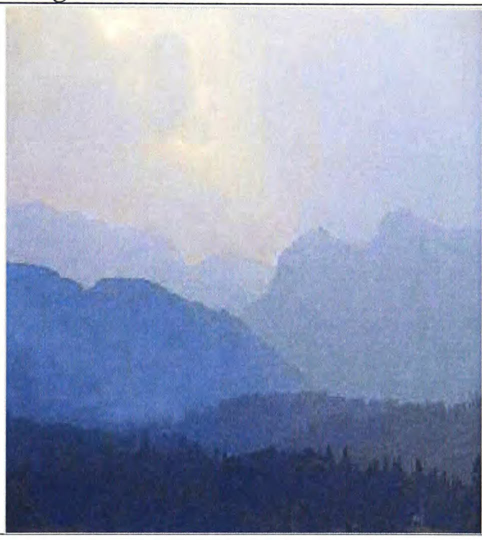
Image 5 : Euler = - 2	Image 6 : Euler = -3	
		Pair 3
Image 7 : Euler = -3	Image 8 : Euler = -4	
		Pair 4

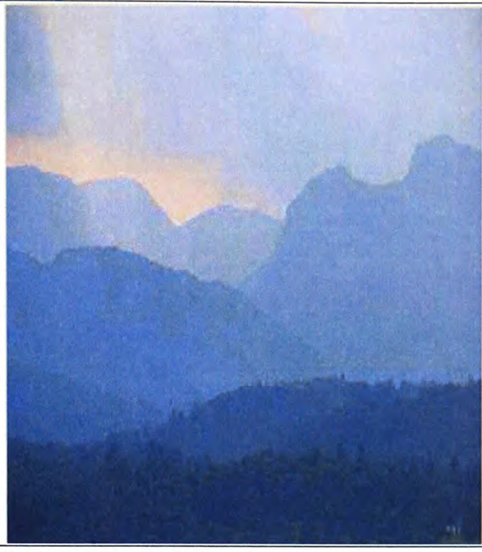
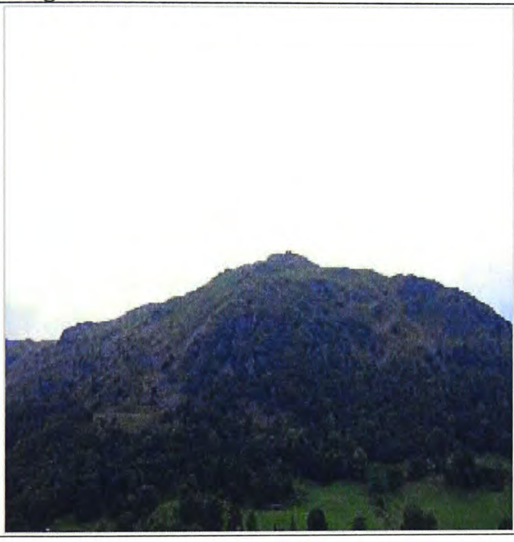
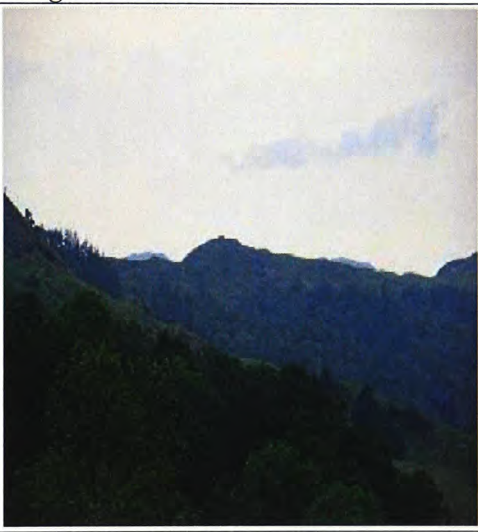
Image 9 : Euler = -4	Image 10 : Euler = -5	
		Pair 5
Image 11 : Euler = 1	Image 12 : Euler =-2	
		Pair 6

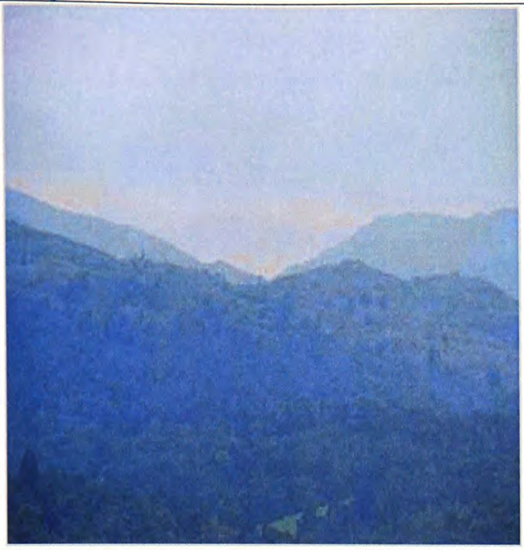
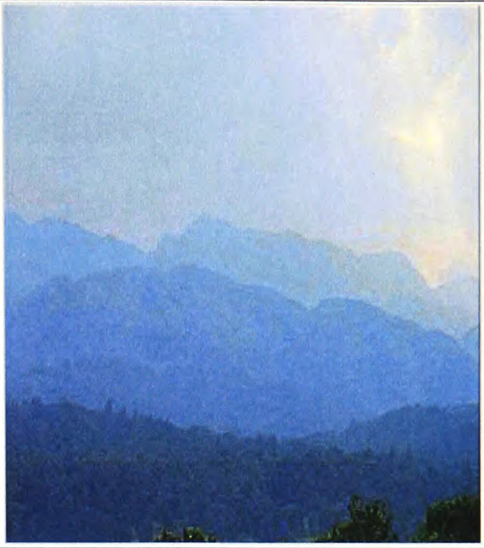
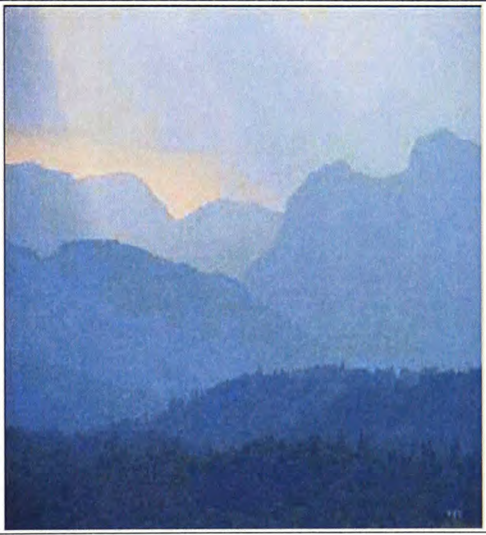
Image 13 : Euler = 0	Image 14 : Euler = -3	
		Pair 7
Image 15 : Euler = -1	**Image 16 : Euler = -4**	
		Pair 8

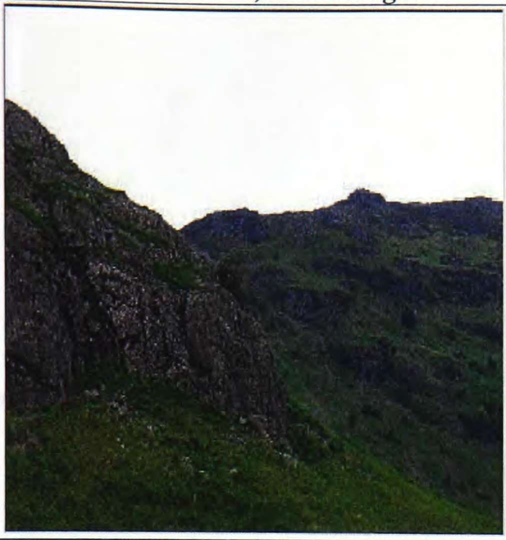
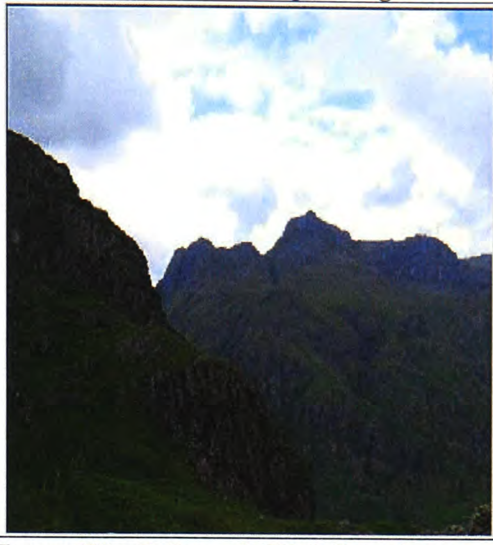
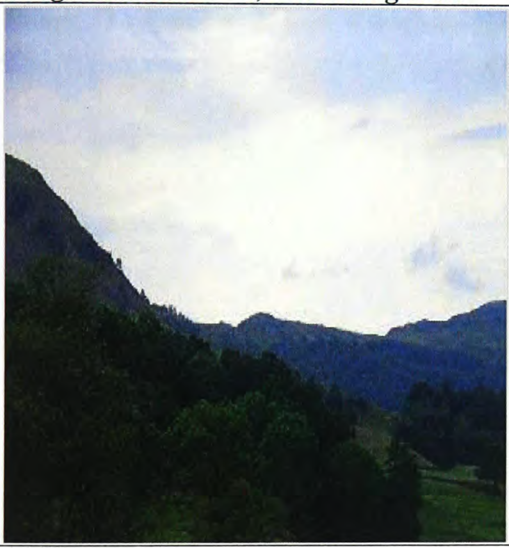
Image 17 : Euler = 1, Low Roughness	**Image 18 : Euler = 1 High Roughness**	
		**Pair 9**
Image 19 : Euler = 0, Low Roughness	**Image 20 : Euler = 0, High Roughness**	
		**Pair 10**

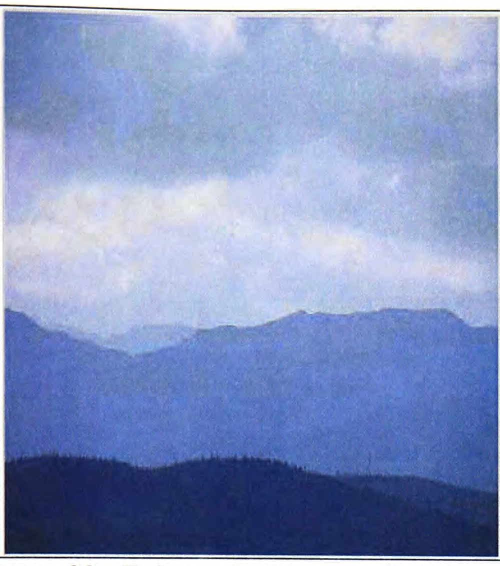
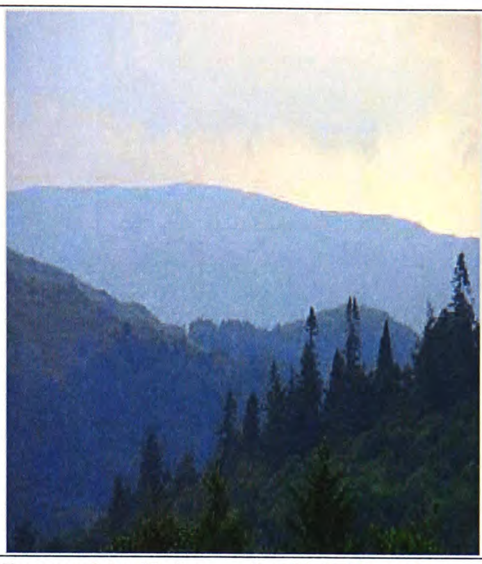
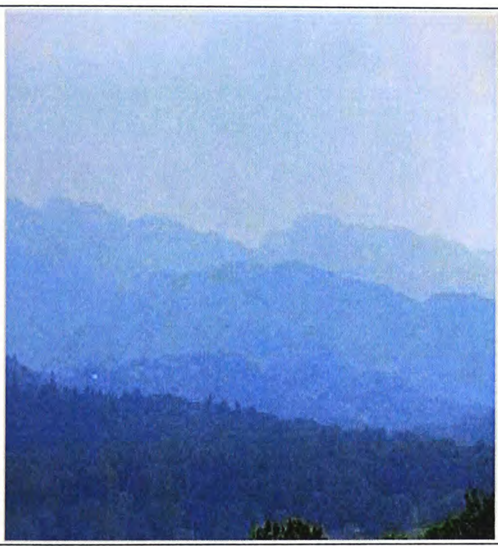
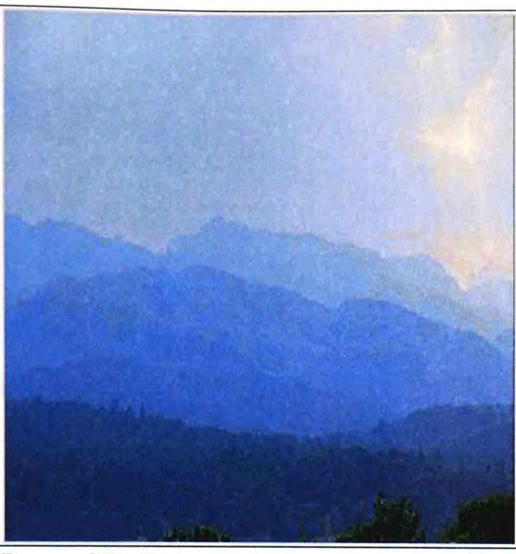
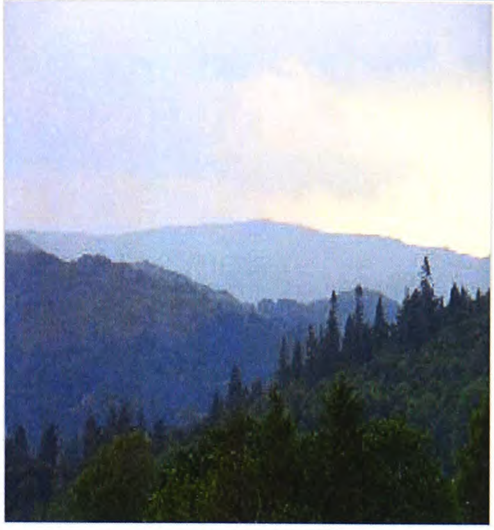
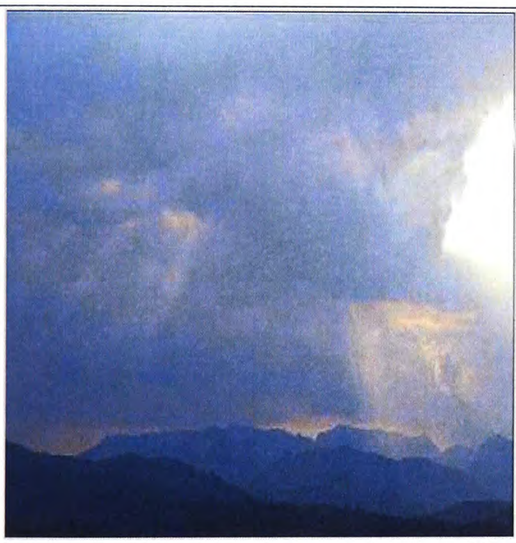
Image 21 : Euler = -1, Low Roughness	Image 22 : Euler = -1, High Roughness	
		Pair 11
Image 23 : Euler = -2, Low Roughness	Image 24 : Euler = -2, High Roughness	
		Pair 12

Image 25 : Euler = -3, Low Roughness	**Image 26 : Euler = -3 High Roughness**	
		Pair 13
Image 27 : Euler = -5, Low Roughness	**Image 28 : Euler = -5 High Roughness**	
		Pair 14