A 3D LANDSCAPE INFORMATION MODEL

USING REAL-TIME 3D GRAPHICS FOR SITE-BASED LANDSCAPE DESIGN

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ABSTRACT

It is possible to construct increasingly realistic computer based three dimensional (3D) models of landscape designs, which when used in interactive visualisations, have been shown to increase engagement and cognitive response. However, they remain underutilised in the landscape design process, due to the time taken to produce a model and the perceived complexity of modelling software.

There would be more reason to construct a 3D model if it could be utilised as more than just a visualisation. Therefore, this thesis explores the hypothesis that it is possible to make virtual 3D landscape models central to the landscape design process.

As the role of 3D real-time graphics amongst more traditional forms of visualisation in the design process remains unclear, a new methodology for examining this as well as data regarding this issue are presented, highlighting an expert user preference for both two dimensional (2D) plans and interactive 3D visualisations.

Given this result and other supporting research, this thesis presents the concept of a 3D Landscape Information Model (3D LIM), defined as an interactive software tool that supports the landscape design process in both the construction and judgment of a landscape design via 3D landscape models. A theoretical framework for key functionality and the usage of a 3D LIM is presented and the development of a prototype 3D LIM based on this framework is described.

A set of distinct simulation techniques to aid judgement of the performance of a landscape design is connected to this prototype through adding a landscape semantic to the 3D model. Firstly, real-time integration of geo-spatial analysis and Bayesian Networks into a 3D LIM is shown to be possible. The 3D LIM is then integrated, in an offline manner, into computationally expensive microclimate and flood simulations. Next, a novel agent based pedestrian and vehicular model is developed that is driven from data held in the 3D LIM landscape system.

Finally, the 3D LIM prototype is extended once more to contain a web server. It is shown that this development allows for on-site viewing and editing of the 3D model via mobile data networks for site surveys and as a possible method for public consultation.

DECLARATION

The work presented in this thesis is original work undertaken by the author between October 2008 and October 2012 at the University of Sheffield. Some of this work has been published separately:

L. Gill, E. Lange, E. Morgan, and D. Romano, "An analysis of usage of different types of visualisation media within a collaborative planning workshop environment," *Environment and Planning B: Planning and Design*, vol. 40, no. 4, pp. 742 – 754, 2013.

L. Gill, E. A. Hathway, E. Lange, E. Morgan, and D. Romano, "Coupling Real-Time 3D Landscape Models with Microclimate Simulations:," *International Journal of E-Planning Research*, vol. 2, no. 1, pp. 1–19, 2013.

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L. Gill, V. Kumar, E. Lange, D. Lerner, E. Morgan, D. Romano, E. Shaw, 2010: *An interactive visual decision support tool for sustainable urban river corridor management*. In: Proceedings of iEMSs 2010, Ottawa, Canada. p. 1438- 1445, ISBN: 978-88-9035-741-1

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LIST OF ABBREVIATIONS

2D	…………………………………………………………..	Two Dimensional
3D	…………………………………………………………..	Three Dimensional
ABM	…………………………………………………………..	Agent Based Modelling
API	…………………………………………………………..	Application Programming Interface
BIM	…………………………………………………………..	Building Information Model
BN	…………………………………………………………..	Bayesian Network
CAD	…………………………………………………………..	Computer Aided Design
GIS	…………………………………………………………..	Geographic Information System
GUI	…………………………………………………………..	Graphical User Interface
GPS	…………………………………………………………..	Global Positioning System
GPU	…………………………………………………………..	Graphics Processing Unit
HTML	…………………………………………………………..	HyperText Markup Language
LAN	…………………………………………………………..	Local Area Network
LIDAR	…………………………………………………………..	Light Detection And Ranging
LIM	…………………………………………………………..	Landscape Information Model
NPR	…………………………………………………………..	Non Photo-realistic Rendering
SWSG	…………………………………………………………..	Sheffield Waterways Strategy Group
UHI	…………………………………………………………..	Urban Heat Island

Chapter 1

INTRODUCTION

3D real-time computer graphics are able to create increasingly realistic virtual representations of actual, or possible future, landscapes. As shown in Figure 1, they are beginning to be used to construct interactive eye level walk-through visualisations for landscape design and planning. However, these visualisations are mainly used as a method of communicating final designs to end-users rather than as an integral part of the design process, often due to the cost of constructing 3D models, as well as the perceived complexity or limited nature of the software tools currently available [1].

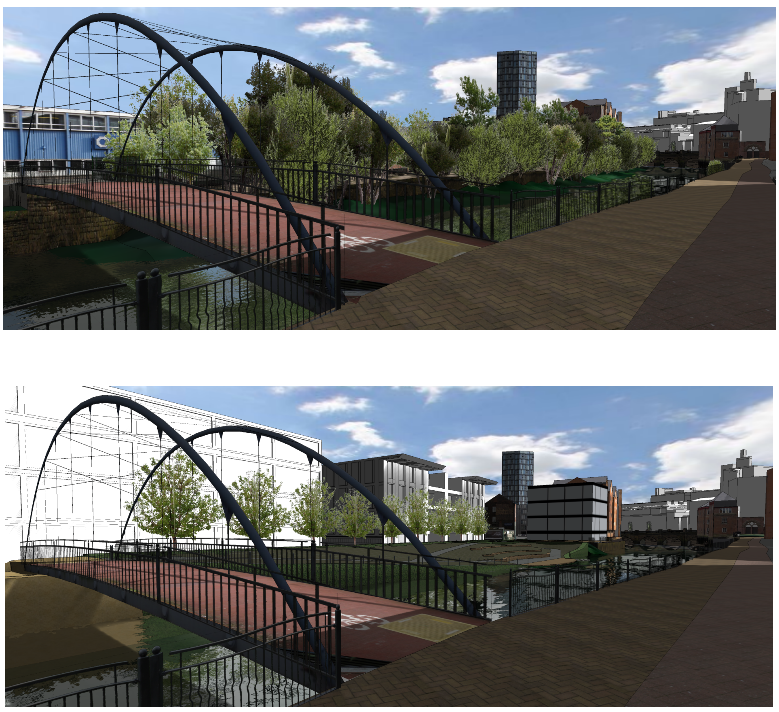

Figure 1 – Different design proposals in an interactive 3D visualisation

Landscapes are dynamic entities and are subject to both natural and human based processes. With this in mind, landscape design and planning processes have developed over time to manage the human response to natural change and their future visions. Regarding landscape change, there is a modern trend towards producing sustainable landscape designs, such as the principles of landscape management enshrined in Article 1 of the European Landscape Convention [2, p. 369].

In the field of architecture, Eastman [3] proposed Building Information Models (BIM). A BIM is a single repository of data about a building and aims not only to inform a collaborative design stage, but also to support the entire life cycle of a building. A BIM contains design geometry combined with attributes, and the supporting software exposes this design data through generic interfaces to enable different analytical programs to integrate the design. The adoption of BIM into industry has been slow, but there are now mainstream products that can be used. Ervin [4] has suggested a similar approach is taken to landscape design in the form of Landscape Information Models (LIM), the idea being that there would be one central model for a landscape proposal that could be used for visualisation, analysis and simulations. Such LIMs are still to emerge however.

Therefore, this thesis examines the development of a 3D LIM that combines real-time 3D visualisations and analysis of landscape performance to aid sustainable landscape management.

1.1 Definition of Terms

In the context of this thesis, it is necessary to define certain terms that will be used throughout this thesis.

A *model* is a description, generally simplified, of a particular system. *Modelling* is the act of constructing a model. Thus, it is possible to construct a model of a landscape using wood or other materials, or through 3D landscape computer modelling, which results in a computerised mathematical 3D representation of a landscape being created. Often, mathematical models can be used to attempt to predict a future state of that system, such as flood modelling.

A *simulation* is created by running a particular set of inputs through a model to produce some predictive results of a future state of the modelled system.

The verb *to visualise* is defined as the act of displaying and interpreting data, possibly generated from a simulation, via a particular medium. *Visualisations* are produced as the result of visualising data. As an example, results of flood simulations are often displayed as a set of 2D plans displaying a flooded area over time. With regards to 3D computer modelling, a visualisation occurs when the computer is given the instruction to render a 3D model to a screen. This would equally be true if the same 3D model were rendered as a physical model on a 3D printing device.

The term "*interactive 3D visualisation"* has been defined as "a simulation employing real time 3D graphics to represent the visual form of an area of landscape in which the user can control the viewing position to freely explore all the aspects of the land form" [5].

1.2 SCOPE OF THE THESIS

Landscape design and planning encompass a large range of activities and can consist of a top-down approach, or a more democratic public participatory process [6, Fig. 31.1]. It can be as generic as creating broad-brush zoning plans for entire cities, or as specific as defining a planting scheme for a park.

Real-time 3D technology tends to apply most strongly to actual physical designs for a landscape, rather than to large scale strategic planning. Thus, this thesis will limit itself to a subset of the landscape planning activities. It will be limited to the process of site-based design, which can be defined as creating a design for adapting an existing landscape to a new configuration. It will then explore development of a 3D LIM software tool that can aid in the process of constructing one or more designs for a specified area of the landscape that can used by individuals or in collaboration.

1.3 CONTRIBUTION TO KNOWLEDGE

This thesis explores the potential for incorporating real-time 3D graphics into the site based landscape design. This is achieved in the following ways. It:

- furthers the evidence base for the inclusion of 3D visualisations in the landscape design process through questionnaire based evaluation. It also develops a novel method centred on video capture of visualisation media usage and applies presence tracking methods inside interactive 3D visualisations to urban design

- develops a theoretical framework that considers the role and necessary functionality a 3D LIM could take within the site-based landscape design process
- provides a novel implementation of a 3D LIM using procedural generation that can perform landscape assessment, demonstrated by linking the 3D LIM data directly to several different styles of analytical modelling (geo-spatial, knowledge based, computationally expensive, agent based)
- offers a method for dissemination of a 3D LIM model to smartphone and tablet devices for on site editing and public consultation processes

1.4 THESIS STRUCTURE

The thesis is separated into chapters, which explore a specific topic related to the overall discussion of the use of 3D graphics as an integral part of the site-based landscape design process.

Chapter 2 details the history of landscape visualization, together with the integration of 3D graphics into this process and possibilities for the future.

Chapter 3 presents the results of two experiments examining the usage of visualisation media by experts in the landscape design process. One experiment explores a new methodology for analysing the use of visualisation media, the second uses a self-reporting technique alongside a procedure for tracking movement in 3D visualisations. Results from both experiments are presented and discussed.

Chapter 4 outlines a theoretical framework for a 3D LIM, defining key features and how these would integrate into the landscape design process.

Chapter 5 documents the implementation of a 3D LIM prototype that provides the fundamental functionality required by the theoretic framework. It outlines the first attempts to include linked analysis into the prototype and concludes with a discussion of the methods used, limitations of the prototype and future work.

Chapter 6 outlines how Bayesian Networks, a form of knowledge based modelling, were integrated into the 3D LIM prototype including analytical feedback, both inside and alongside the 3D model.

Chapter 7 looks at how the type of model that can be classed as too computationally intensive to be used in the real-time feedback can still be integrated into the 3D LIM prototype in an offline manner.

Chapter 8 describes a novel force based pedestrian and traffic model implemented on the GPU using an agent based approach. It details how the input to this model can be created from the 3D LIM prototype.

Chapter 9 examines how the data held in the 3D LIM prototype was delivered to mobile devices on site and how this could feed into site survey and public participation activities.

Chapter 10 contains the overall results, discusses these and future directions and presents the final conclusions drawn from the research.

Chapter 2
LANDSCAPE MODELLING AND VISUALISATION

This thesis combines elements of landscape design and computing, so to give a context to the research presented herein, Section 2.1 gives a brief introduction to the history of landscape visualization. Section 2.2 provides detail on the methods for construction of 3D models for real-time visualisation. After this, Section 2.3 discusses how interactive 3D visualisations fit into the landscape design process. Finally, Section 2.4 presents a summary in which the potential in the future for interactive 3D models and visualisations are explored.

2.1 HISTORY OF LANDSCAPE VISUALISATION

For reasons of artistic merit or decision-making, people have always striven to capture the essence of both natural and built environments that surround them. Wall paintings created by the ancient Egyptians capture long lost gardens in pictorial form, such as the garden of Sebekhotep found on a tomb wall in Thebes [7, p. 17]. These early images mix together plan, elevation and bird's eye viewpoints, making it hard for the modern eye to interpret [8]. However, the acceptance and consistent usage of perspective in the Renaissance period contributed to more accurate depictions of landscapes, leading to the creation of images that resemble the real world rather closely. Audiences in the late 18th and early 19th century were amazed by the creation of Eidophusikons, 'moving' pictures created by 18th century English painter Philip James de Loutherbourg, dioramas or large-scale panoramic paintings. These can be seen as the equivalent of IMAX cinemas of today. Related to these developments is a more abstract form of landscape visualisation; cartography, which also has a long and rich pedigree[9].

Historically, capturing landscapes in images was driven by artistic, political or martial needs, but it is also possible to impart how landscape may come to look through these methods. Important early examples of this are the 'Red Books' of landscape architect Humphry Repton (1752-1818), who created water colours of existing landscapes and his future vision of changes, utilising a system of painted overlays on flapped hinges [10]. These provided his clients with an easy to use 'before' and 'after' comparison of a proposed change to their estates.

As photographic technology developed and became affordable at the turn of the 20th Century, it became possible to capture existing landscapes far more rapidly than via drawing or painting. As a technical refinement the *photomontage* technique allowed new landscape features to be overlaid on to existing photography through manual etching or drawing on the photograph.

In addition to the two dimensional representation of landscapes, physical scale models, constructed from wood, card and so on, have been used to capture the spatial relationships of landscapes (Figure 2). They have been used to simulate journeys through landscapes using microscopic cameras, e.g. to record on video tape. While scaled models are normally used in practice (Figure 2), on occasion even a 1:1 representation – that is, a real world model - is produced, as shown in Figure 3.

Figure 2 - Scale model, Yantai, China; note the size of the person in the door at the top left corner. © Eckart Lange 2013

Figure 3 - Berlin, Potsdamer Platz, 1:1 scale model © Eckart Lange 2013

Towards the end of the 20th Century the availability of desktop computers allowed digital techniques of landscape visualisation to become more pervasive in presenting and conveying change to landscapes. Rather than hand-drawing plans, landscape architects began to employ computer software to draw, display and print their designs. With the advent of digital photomontage software, photographs could be composited together [11] and this technique has flourished since.

Computer Aided Design (CAD) and Geographic Information Systems (GIS) software tools have had a significant impact on the visualisation of landscape, allowing the creation of 3D landscape models on computers. Initially, due to the constraints of computer processing power, these models were used to support the creation of more accurate photomontages as well as to create pre-rendered animated walk-throughs of places, which give the viewer a sense of motion through a landscape [12]. Also, with the ability to create and analyse complex spatial data, it became possible to deliver consistent high quality plans and maps of landscape change. The maps and plans output from this style of software are now commonplace in planning proposals. As remote sensing techniques have developed, vast data sources for mapping and aerial photography have become more common. From the inception of GIS, they have remained a specialist tool, but within the last decade, geographic data sources have become accessible via the internet from corporations, such as Google Maps / Earth[1] and Microsoft Bing Maps[2], or from open source initiatives, such as Open Street Map[3].

Although the digital revolution had led to a radical change in the techniques and tools that could be used to create landscape visualisation, the results still present snapshots of landscapes. These stylised representations of landscapes are useful to communicate information about landscape change, but they do not mirror the way people experience the real world. People rarely take a bird's eye view of a landscape and landscapes are not static; they are experienced dynamically and change over time. For non-specialists, abstract and fixed representations can prove difficult to interpret and the choice of viewpoints and what is visualised in them may not be entirely representative of a scheme, especially if the visualisations are designed to market an idea. For example, Tufte [13] highlights how Repton altered scales and added unnecessary embellishments to some of his before and after drawings. So, there exist two possible forms of disconnection from a portrayed design: visualisations constructed in a misrepresentative way (deliberate or not), or a failure of viewers to interpret the visualisation correctly. This applies to the whole range of analog or digital landscape visualisation.

In recent years, there has been a conjunction of specialised computer hardware and computing methods dedicated to the provision of real-time graphical environments, driven by the need for higher fidelity visualisation and simulation. This has allowed people to create 3D landscape models that are becoming more visually complex and interactive, finally allowing people to move freely around virtual spaces taking any viewpoint they wish to observe in future landscapes, so giving rise to detailed real-time eye level walk-throughs [5]. These provide far more in-depth exploration of the spatial nature of future designs.

Hence, a major question is how best to incorporate these interactive 3D technologies as suitable visualisations into existing practice and workflows to better support design of and communication of

[1] http://maps.google.co.uk

[2] http://www.bing.com/maps

[3] http://www.openstreetmap.org

landscape change. To begin to answer this, it is necessary to understand how interactive 3D landscape visualisations are constructed.

2.2 CREATING INTERACTIVE 3D LANDSCAPE VISUALISATIONS

Construction of an interactive 3D landscape visualisation requires three basic elements: a 3D model of an area; software that can take this model and display it in real-time; and computer hardware that allows the software to operate efficiently.

Whilst there are an increasing number of software packages available (Simmetry3D[4], Lumion[5], Biosphere3D[6]) or converted computer game engines [14] that allow real-time interaction with 3D models and the requisite computer hardware is becoming cheaper, a major difficulty for creating interactive 3D visualisations is that of model construction [1].

When creating a 3D model, it is necessary to collect enough data that will allow the creation of the model to the level of detail required. Ervin [15] suggests that a digital landscape model can be broken down into six elements: Landform; Vegetation; Water; Structures; Animals; Atmosphere. To elaborate, structures include all built form and infrastructure, such as roads, while the 'animals' category includes humans. To this list, certainly for visualising modern urban environments, a further category of vehicles should be introduced.

Landform data can be acquired from a variety of remote sensing sources, but the more detailed the source the more accurate the resultant model will become. Ribarsky et al. [16] noted the increasing availability of aerial and ground based Light Detection And Ranging (LIDAR) capture systems that allow the acquisition of accurate location and physical form datasets that can be used to generate urban models. Data derived from remote sensing data can provide a starting point for interactive modelling techniques.

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[4] http://www.simmetry3d.com

[5] http://lumion3d.com

[6] http://www.biosphere3d.org

A common practice is to overlay terrain models with the relevant aerial photography to present contextual information on the landform, as happens in Google Earth. This works well when the viewpoint of the terrain is far away, but has its limitations as the viewpoint gets close to the terrain. The foreground of visualisations is noted as being important for the degree of realism [17]. This implies that it is important to add as much foreground detail as is possible to landscape visualisations, especially if the interactive 3D visualisation is to provide eye-level walk-throughs.

Atmosphere can be defined using simple effects, such as placing a "sky box" of appropriate textures that surround the landform model. Boulanger et al. (2008) [18] demonstrated dynamic real-time lighting of natural scenes, where lighting can be interactively changed to provide realistic conditions. Vegetation, structures, water and animals can be placed on top of the landform model in their corresponding positions in the model, which can often be derived from existing GIS vector map data.

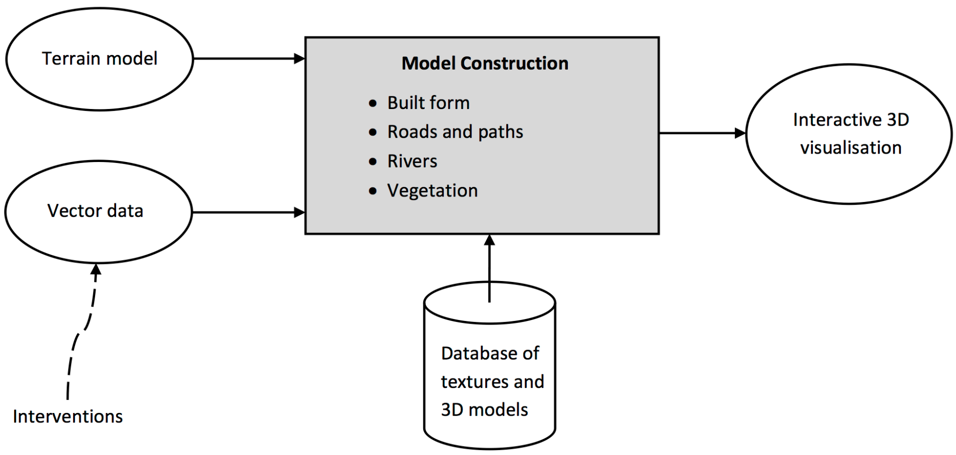

Figure 4 - 3D landscape model construction [5]

Once all the data required for the modelling is collated, then the most traditional approach to the construction of a digital landscape model is to composite all the elements of a model by hand using software to create generic 3D models [19]. This process is illustrated in Figure 4 and shows that a reference terrain model is combined with vector GIS data, such as land usage data, to create a base model for positioning of 3D models of structures, natural features, vegetation and animals. Alterations to vector GIS data are used as a method for injecting proposed design changes to a site, or "interventions" in the diagram, into the visualisation.

Libraries of 3D models of trees, plants, animals and vehicles exist and can be re-used in this compositing process, but there always remains site specific elements, such as built form, that require the construction of bespoke 3D models.

The cost of this modelling by hand is linked to the complexity of the model; as the detail increases, the amount of construction time required naturally increases [20]. This has led to the drive for the development of methods that reduce the time to create models of landscapes. Hoinkes & E. Lange [21] developed an automated process of creating 3D models from 2D data sets. Such a system requires a library of suitable 3D models to be available, e.g. vegetation elements and structures, like power lines, as well as built form. In recent years, commercial GIS programs, such as ESRI ArcGIS 3D Analyst[7] have also begun to contain such functionalities.

Procedural generation of models, or procedural modelling, is the process of algorithmically constructing models. In other words, a computer uses a pre-defined set of rules to take an input set of data and transforms this to the resulting model as an output. It is often used to create individual elements of models, such as built form Wonka et al. [22], or whole virtual environments, such as the IMAGIS system [23] that generates large scale 3D landscape models based on geo-referenced data.

Ervin's final category of animals and the new category of vehicles in interactive 3D landscape models tend to be static or at most animated in simple fashion. Typically, real world movement patterns are not accurately represented. Improved animation of animals and people in interactive 3D landscape visualisations and the perception of these elements remains an area to be researched.

2.3 LANDSCAPE DESIGN AND 3D INTERACTIVE VISUALISATIONS

Given that real-time 3D landscape models of a design proposal can be created, it is necessary to ask how these fit into landscape design theory. Accordingly, consider the following quotation:

[7] http://www.esri.com/software/arcgis/extensions/3danalyst

> *"… designers need to construct "a virtual world", a model of what they know about a site and program, which allows possibilities to be tested quickly"* Lynch and Hack [24, p. 128]

Back in 1984, Lynch & Hack were referring to 'virtual worlds' in the context of exploring change and designed alterations to a landscape. They speak of the construction of 'a virtual world' (for clarification purposes, referred to subsequently as the *mental model*) within the mind of the designer. They propose that diagrams and physical models, traditional forms of landscape visualisation, aid the construction of this mental model. However, since the time of this quotation, there have been many advances in technology which have led to the possibility of using real-time 3D models within the design processes for landscapes [25, p. 2005]. In essence, it is now possible to create digital virtual worlds that support Lynch's mental models, using interactive 3D landscape models.

Also, interactive 3D visualisation techniques fit well in the Steinitz model of Landscape Change, which breaks the process of design down into three passes through defined stages of modelling [26], as shown in Figure 5.

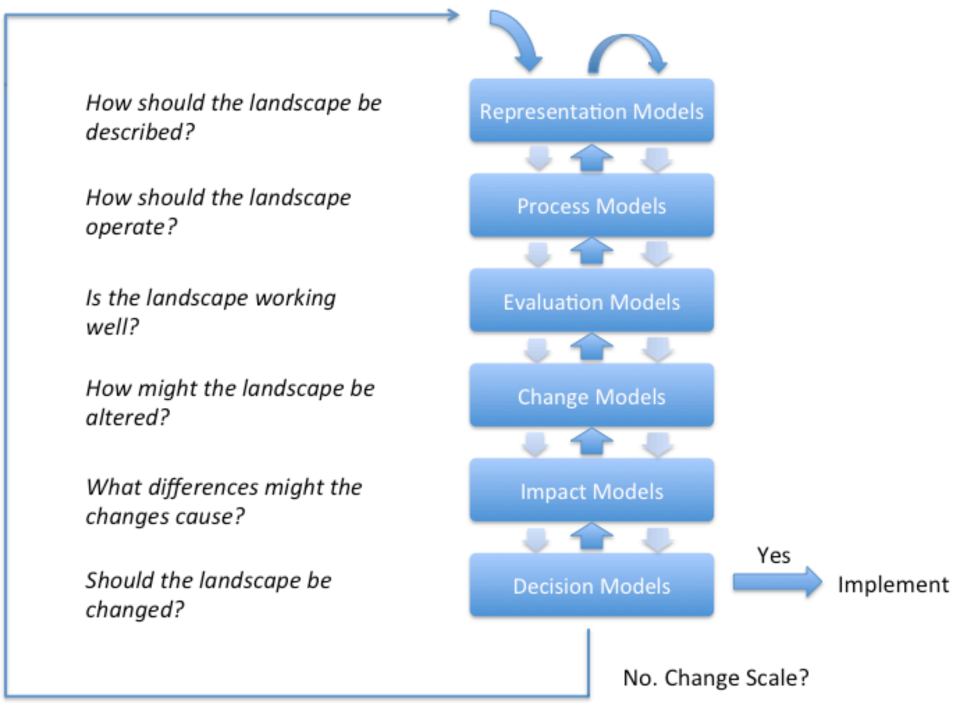

Figure 5 - Steinitz Model of Landscape Change [26]

At the level of Steinitz' Representation Models and Change Models for analysis of spatial alterations 3D landscape models can help designers answer the questions '*How should the landscape be defined?*' and '*How may the landscape be altered?*'

It is clear that, by enhancing the mental model of a designer, interactive 3D landscape visualisations have a place within the individual design process, but visualisations also present a method for aiding communication between interested parties. Kibria et al. [27] state that when viewing visualisations, people bring their education and experience to bear on the model. By collecting together designers, experts and stakeholders in collaborative design workshops and providing interactive 3D landscape visualisations, there is potential to further improve the mental models of each participant through discussion. The ability freely to explore the spatial nature of landscapes gives interactive 3D visualisations the power to support discussion revolving around a mental model of a participant, which in turn may increase the comprehension of the other participants. By creating discussion, design trade-offs can be explored, which should lead to better design decisions and more transparent planning processes.

At present, interactive 3D visualisations of landscape are mostly seen as an endpoint of the design process rather than as a design tool for communication between the designer and the stakeholder. The easier it is to create and visualize 3D models, the more likely it becomes to include interactive 3D techniques as *part* of the design process. Flexible 3D models exist that allow designers to edit and change the underlying 3D landscape model, such as in the Smart Terrain system [28].

Landscape planning processes are methods for legitimising and controlling anthropogenic impact on the environment (e.g. Lange & Hehl-Lange [29]). These processes have become more organised and prescriptive over time but (supported by international initiatives, such as the Rio Declaration on Environment and Development) certainly in Europe planning authorities are becoming increasingly democratic, attempting to take account of different views of people and organisations that would be affected by any proposed changes.

Consultation in landscape planning has long been supported by the more established visualisation techniques, such as plans, sections, and photomontages. However, as people with less exposure to the interpretation of spatial plans are increasingly being consulted as part of the design process, interactive 3D visualisations may be able to play an increasingly important supporting role. With the inclusion of interactivity in 3D landscape visualisations comes the ability for people to take control over the visualisation, such as the ability of move anywhere within the model (Figure 6). Therefore, there is the potential to deliver far more meaning to the user than a two dimensional image created by someone with their own perspective and agenda. After using interactive 3D visualisations in this collaborative manner, Schroth [30] concludes that interactivity in visualisations contributes to better understanding of scenarios by participants and to building credibility and consensus within the landscape design process.

Figure 6 - Interactive landscape model allowing stakeholders to take control over the visualisation © Eckart Lange 2013

Nonetheless, interactive 3D landscape models are not necessarily going to replace other forms of visualisation, but can be used to augment more traditional forms of landscape visualisation to support the planning process. For example, if some people find it difficult to interpret plans, one of the most common forms of visualisation of landscape change, but are comfortable looking at 3D images, then providing easy to navigate links between these two forms of visualisation may improve their understanding of designs.

Just as the previously mentioned Egyptian garden art contains a confusing mix of perspectives which may obfuscate meaning within a drawing, so there is a danger of misrepresentation using modern visualisation techniques. A longstanding goal of real-time computer graphics is to increase the realism of the images created. However, the more realism there is in an image, the more likely it is to be accepted as final. Therefore, in a landscape design process, it is advisable to adapt the degree of realism to represent adequately the progress of the design process [31]. Computer based models should take this visualisation of uncertainty in designs into account. Therefore, despite having the technology to show visualisations that are increasingly photo-realistic, it should not be used simply because it is possible [25].

2.4 SUMMARY

A possible avenue to take for mitigating 'over realism' in visualisations is that of Non Photo-realistic Rendering (NPR). This is a set of computer rendering techniques that offer a way of presenting 3D landscape models in more abstract form. Images can be automatically generated from one model to look as if they have been sketched [32][33], or drawn in a cartoon style amongst other effects [34]. However, despite their resemblance of hand-drawn sketches there is as yet little understanding of how these representations of landscape may be perceived by participants of the planning process.

There are also a number of interesting uses for these interactive 3D models beyond that of representation of spatial change. Increasingly, non-visual data is being included with these models to increase the amount of information that can be communicated to the viewer. Thus, with the addition of context specific information into the visualisation it is possible to use the same models in other stages of the Steinitz model. For example, if a model were to be created altering a river channel to improve flood protection to display new flood levels visually, then this would allow the interactive visualisations to support the Process and Impact Model stage.

One approach to this is to overlay a 3D landscape model with coloured geo-spatial data sets. This visualisation of non-visual elements allows the viewer to consider observed data within a 3D context, which may provide more insight into the data. Hehl-Lange [35] demonstrated this technique with the overlay of ecological data, such as habitat use of green woodpeckers or visualising bat flight paths in 3D, within a landscape model. Isaacs et al. [36] used falsely coloured built form to indicate individual building energy usage sustainability assessment within their interactive tool, S-City VT. Morgan et al. falsely coloured a 3D landscape model with a density function derived from bird sighting surveys, which was taken a step further by adding bird calls to the model with the frequency of calls based on the same density function [37]. As the user performed an eye-level walk-through, they would experience bird calls based on observed data. Nichol and Wong [38] presented a software tool that takes a 3D CAD model and applies a heat balance simulation to examine surface temperature distribution. This tool allows generic input and linked visualisation, but the base model still has to be manually created within the CAD system.

Regarding Ervin's animal, human and vehicular elements of a landscape and the current static nature of their visualisation, the field of Agent Based Modelling (ABM) may provide realistic simulations of natural behaviours.

ABM defines a population of agents and then applies rules to these individual elements of the simulation. It is the interaction of these individual units that produces overall emergent behaviour in the simulation that can otherwise be too difficult to model, such as animal flocking [39] and crowd simulation [40]. Cavens et al. [41] applied this technique to predict recreational behaviour of hikers in the Alps using a 3D landscape model, allowing agents to react to their physical environment.

In the field of architecture, there has been a movement from traditional 2D and 3D CAD techniques to Building Information Models [3]. These create a single repository of information about a building, which supports the lifespan of a building from design conception, through construction to on-going maintenance. A BIM is built from basic components, such as walls and windows, which know how to draw themselves in both 2D and 3D. To create the BIM, these components are combined in 3D using parametric constraints, which form a structure to reflow elements when designs are altered. As each component can also hold non-visual information, analytical tools have been developed that can operate on the BIM, such as creating costing schedules. One of the stated advantages of creating this form of 3D model is that spatial design errors are reduced at the planning stage, rather than propagating to the construction stages.

An increasingly popular term is that of "geo-design", which is still ill-defined, but the name suggests that efforts should be made to combine geographical data with design, rather than just for representational purposes [42]. In that regard, Ervin has suggested that a similar approach to BIM is taken to landscape in the form of LIMs [43], the idea being that there would be one central database for a landscape that could be used for visualisation, analysis and simulations. Whilst Laycock & Day [44] suggested further work should take place integrating procedural modelling with more standard techniques to create a 'memory efficient realistic urban model', all of these approaches are still working towards the development of an integrated system. This system would not only generate the 3D landscape models and render real time views of a large area of landscape, but also have ability to zoom into detailed areas and provide functionality for editing at site level or strategic scale.

While this thesis was being constructed, procedural modelling has been linked to GIS data sources with the acquisition of the procedural modelling software CityEngine[8] by GIS market leader, ESRI. This system allows the generation of buildings and zoning models from geographical data and numeric interrogation of these models, but does not offer interactive landscape visualisation or editing.

If interactive 3D landscape models that can be changed easily are married with predictive models and simulations, then it will be possible to develop 3D LIMs that are capable of both analysis and simulation of the effects of change and the visualisation of the results of these within a 3D model. Bishop et al. [45, p. 2009] suggest just such a linkage for an interactive visualisation interface for forest management scenarios that would allow the user to simulate different management strategies for forest management over long time periods whilst seeing the visual effects on forests in the landscape. Piper et al developed an analytical system for 3D terrain modelling using clay and a laser scanner to provide a tangible interface, but the system is limited to surface modelling only and suffered from occlusion when a user altered the clay model [46].

One of the major hurdles to public participation in landscape planning is the dissemination of the information to the population at large. Traditionally, planning departments hold the records pertaining to landscape proposals and to distribute this information formal planning meetings are organised, or documentation may be sent directly to the public. Widely adopted connectivity to the internet has altered this by providing online access to planning documents through local governmental planning portals. However, these do not yet provide an avenue for publishing imagery from interactive 3D landscape models, as these tend to be locked into bespoke computer graphic hardware and software that make it difficult to integrate with the online portals.

In 2001, Rakkolainen and Vainio [47] examined the usefulness of 2D maps and 3D models in a mobile environment consulted for navigation of an unknown urban environment. The results from their trial showed both 2D maps and 3D elements were interchangeably consulted by participants. They were hampered however by the lack of computation resource in the handsets available to them, but predicted the arrival of more computationally powerful devices. Nowadays, new opportunities arise for transmission of landscape visualisations with the advent of 'smartphone' technologies that can

[8] http://www.esri.com/software/cityengine

derive their location, have high resolution screens, internet connectivity and enough computing power available to render graphical images [48]. These devices are becoming increasingly commonplace and present an opportunity to transmit landscape visualisation to the public in an easily accessible manner. This has been demonstrated with 'apps' that can overlay information on video feeds, presenting augmented reality (e.g. Layar[9]) and apps that can present visualisations of future scenarios whilst walking through the area that would change [49]. It would seem for landscape architects, architects and planners that the ability to disseminate interactive 3D visualisations of their proposals via smart phones would be highly advantageous in reducing costs of delivery and increasing inclusiveness in decision making.

In summary, it seems that now more than ever it is possible to create detailed imagery of possible changes to our environment through interactive 3D landscape models, especially with techniques like procedural generation. Combine these visualisations with the mobile phone method of dissemination that is becoming available and landscape visualisations will be consumed by more interested parties in more ways.

Moreover, there are suggestions in the literature that 3D landscape models should be used for more than just visualisation. Interactive LIMs may facilitate the creation of visually attractive, sustainable environments and these databases would serve as a historical record of our world and our values. However, there is still little available research on how to implement such systems.

[9] http://www.layar.com

Chapter 3

INTERFACE RESEARCH

As a step towards creating a 3D LIM, it is imperative to understand how designers might want to use real-time 3D graphics within the design process alongside other forms of landscape visualisations.

Section 3.1 presents a summary of research related to the use of visualisation media in the landscape design process.

As part of a larger study in which a group of experts judged the sustainability of a set of contrasting landscape designs, Section 3.2 details how a questionnaire based approach was used to ascertain ratings given to a set of landscape visualisation media. In addition, a method for tracking user movement inside an interactive 3D walk-through and subsequent visualisation of this movement is outlined.

Section 3.3 provides a novel methodology and experimental results for examining in detail the usage of different landscape visualisation media as part of a collaborative design process. Finally, Section 3.4 discusses the experimental findings and how they may be relevant to the creation of a 3D LIM.

3.1 RESEARCH CONTEXT

Tufte [50] defines visualisations as a more suitable medium for clarifying certain complex data than the written word or voice alone can offer. The role of planning has evolved over the years to become a communication between planners and communities, where planners guide the communities to decisions [51]. Thus, with planners needing to explain multifaceted proposals efficiently, forms of landscape visualisations are increasingly common. Sheppard [52] posits that landscape visualisations will provide up to four responses in a viewer: cognitive, affective, behavioural and physiological. As a proposal passes through the various stages of design and consultation, these responses to visualisations could differ significantly for the same person over time. Certainly, the level of detail has an effect on the viewer [17][53] and technical and non-technical participants may perceive the same visualisation differently [27]. Given this uncertainty to response, Sheppard [52] states visualisations have the capacity to bias decision-making and therefore must be defensible, including only relevant and accurate information.

Planning proposals occur at a variety of scales from large scale regional planning down through site level to individual elements of the landscape and Orland et al [54] suggests that visualisation tools should be able to handle all scales consistently, but there is little theory available on the suitability of different types of visualisation for each scale. However, this investigation is limited in scope to the evaluation of usage of visualisation media in a collaborative planning context for site scale, where interactive 3D visualisation is most likely to be offered.

Landscape visualisations may be viewed by individuals, or within a participatory group setting. Having visualisations available within a group session allows people to refer to elements of that visualisation to support their discussions about a proposal. In this case, the visualisation acts not just as a conveyor of information, but as a reference point for all members of the group too. Several studies have examined the perception or usage of media types within this participatory planning process. Al-Kodmany [55] observed the freehand sketching, GIS and computer based photo-montages in a public consultation process, concluding that at the design stage defining context using GIS and abstract sketches proved useful to the process, whilst more realistic imaging was important at later stages. Lewis and Sheppard [56] ran a study to attempt to understand the difference in cognition between static 3D digital photomontage visualisations and GIS based mapping. Using a structured interview technique, they presented a small sample of a First Nation community with differing forestry and riparian scenarios. This was a limited study dealing with a non-technical audience, but Lewis and Sheppard conclude that both forms of visualisations should be available when presenting scenarios to aboriginal audiences. Videos generated from physical models were compared to real world videos and automotive tours of a research site in a large study by Feimer [57], which asked participants to rate the study site using a variety of adjective based techniques, but did not establish any significant effect on perception of the site based on the media used. Bates-Brkljac [58] examined perceptual differences between urban development communicated by hand drawn perspective drawings, painted water colours, digital photomontages, and images created from rendering 3D models using semantic differential scales, finding overall that the computer generated images were perceived as more accurate and realistic. According to Al-Kodmany [59], the literature surrounding usage of media in public participation suggests that a combination of traditional and computer based media types that complement each other is the overall best solution. Although these studies have begun to analyse the usage of differing types of visualisation media, they seem inconclusive in proving a most suitable form or combination of forms, and then establishing clear theory to guide real world practice. This body of work also does not yet consider how newer interactive 3D visualisation techniques fit.

Interactive 3D visualisations have previously been used within participatory planning workshops successfully for a variety of different landscape scenarios, such as positioning of wind turbines [60], forest planning [61], flood management [62], including game style walk-throughs of urban river corridors [5] and gardens [63, p. 200]. Indeed, Schroth et al [64] concluded that interactivity of movement within 3D visualisations was indeed useful to consultation within the planning process.

There is evidence that interactive 3D visualisations have an effect on decision making. Bishop et al [65, p. 2001] ran an experiment using an interactive forest environment that concluded people make different choices when presented with an interactive visualisation rather than similar static images. There is also research suggesting that interactive 3D landscape models are preferable to other forms of visualisation media. Appleton and Lovett [66] examined differences in perception between static images and interactive 3D models of rural environments and concluded that the landscapes were "easier to imagine" using the interactive 3D visualisations, but there was little difference between presenting the model on a standard monitor or projected on to a large screen. Salter et al [67] analysed the usage of GIS based interactive 3D models coupled with sustainability indicators within a planning workshop. They found that being able to interact with the visualisations was highly rated by participants of their workshop. This previous work establishes that interactivity of 3D visualisations is useful, relevant to the participatory planning process and is rated highly.

Thus, it could be hypothesised that *participants within a small participatory group setting will prefer to use interactive 3D visualisations of a site scale proposal over more traditional methods for communicating proposals*. The aforementioned studies rely heavily on self-reporting, rather than establishing methods of quantitatively examining the usage of media types. The implicit assumption in this technique is that *there is a strong correlation between the ability of the participant to be able to rate their use of a media type and their actual usage of that media type*.

There is little data to inform these hypotheses on the usage of interactive 3D visualisations alongside other visualisation media types. Therefore, two experiments were run to gather data.

3.2 MEDIA CHOICE EXPERIMENT 1

An experiment was conducted to examine the self-reported preferences for visualization media, given the presence of interactive 3D visualisations amongst a set of other visualisation media. This experiment was conducted within the context of a distinct larger experiment that was examining sustainable re-development of urban riversides [68].

For this larger experiment, a series of visualisation media and documentation had been created, which illustrated a series of different treatments for an urban riverside area. Each design was created to represent a different style of landscape that would highlight divergent elements of sustainable management [69]. There were four scenarios created: the status quo; the local council regeneration option; a hard urban form and a flood relief channel (shown in plan form in Figure 7).

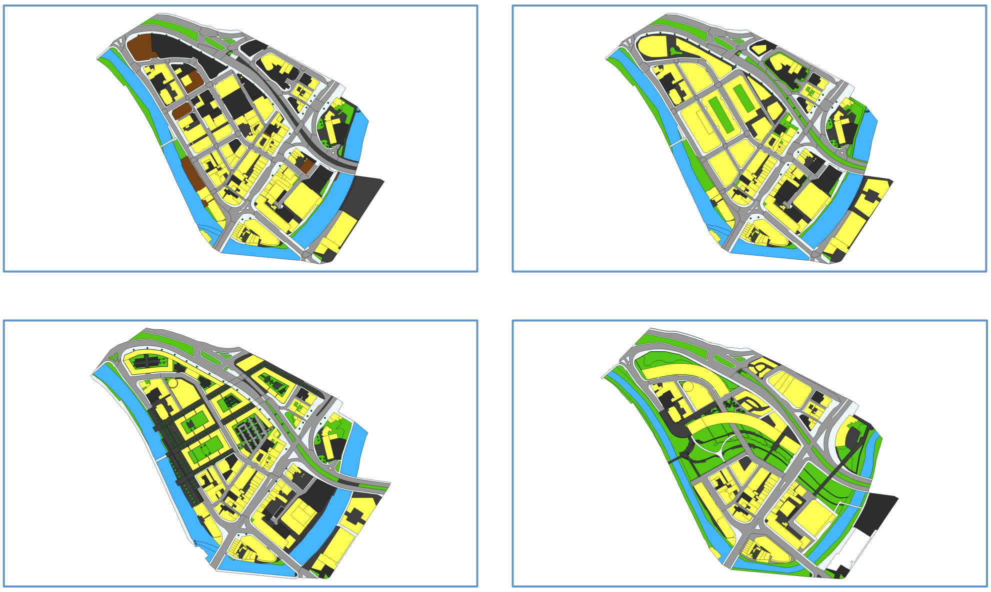

Figure 7 - Plans showing the four urban form designs (clockwise from left) status quo, local council regeneration, hard urban and flood relief channel

To give the reader an understanding into the differences between each design, the same viewpoint taken from an interactive 3D landscape model of each of the designs is shown in Figure 8.

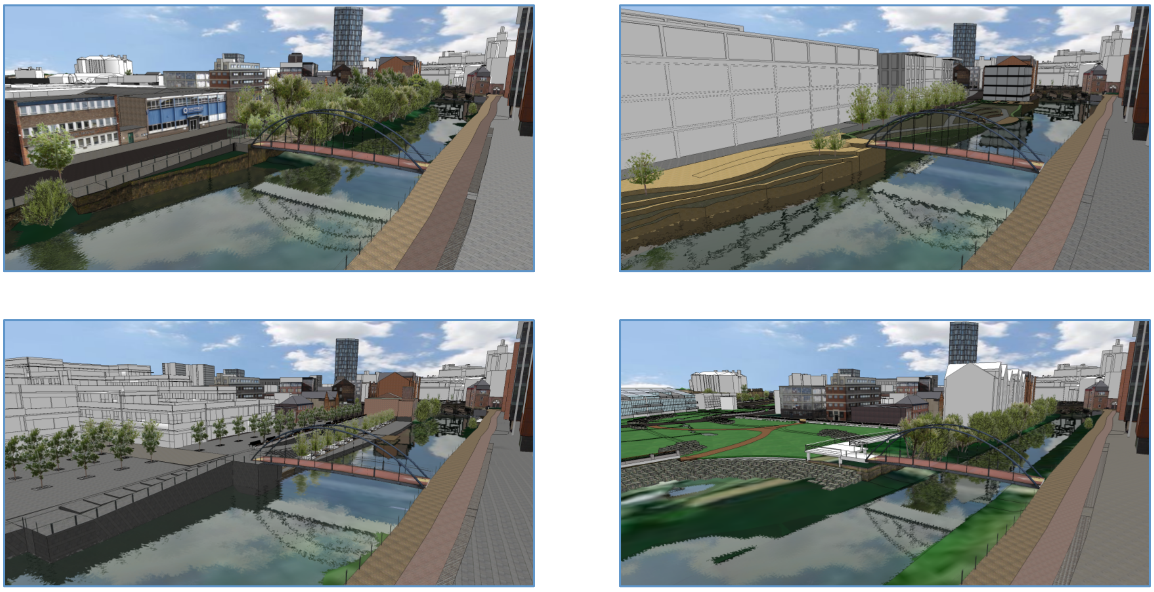

Figure 8 – Screenshots from interactive 3D visualisations of the four available sustainability designs (clockwise from left) status quo, local council regeneration, hard urban and flood relief channel

Alongside documentation for each scenario, the following visualisation media were created:

- A set of 2D plans
- Photomontage of a viewpoint
- Walk-through video
- 3D landscape model

The 2D plans were produced for each scenario detailing different categories of land usage from building height to vegetation coverage. The 2D plans were created from Ordnance Survey mapping data, which was then altered and coloured in Arcmap[10] GIS. The 3D landscape model was constructed manually using Simmetry 3d software package. The photomontage was produced in Photoshop[11] using a composite of existing imagery and screen shots from the interactive 3D visualisation.

The participants would be exposed to interactive 3D visualisations and allowed to dictate movement within these virtual environments. Within video games, it is possible to collect data that enables

[10] http://www.esri.com/software/arcgis/arcgis-for-desktop

[11] http://www.adobe.com/uk/products/photoshop.html

analysis of gameplay metrics. For example, in games with 3D virtual environments, it is possible track the movement and state of players to collect data about the playability and design of those virtual environments. Drachen and Canossa describe a flexible system to connect and visualise the data collected in this manner to GIS to perform spatial analysis [70]. Using this system, they visualise the cause of player death within a virtual 3D environment using heat maps. Furthermore, Chittaro et al developed VU-flow, a comprehensive program that analysed and visualised the movement of users in virtual environments by post-processing movement data into a 2D rasterised version of the environment. They suggest this methodology could be applied to urban planning [71]. Therefore, the movement of participants within the interactive 3D walk-throughs would be logged to produce a data set of movement, which could be subsequently visualised.

3.2.1 Experimental Setup

The overall experimental design, of which this media choice experiment was part, was designed to capture how sustainable each of the scenarios would be rated by a set of experts. These experts (n=32; 17 male, 15 female) were chosen to represent a range of expertise across social, economic and ecological areas (8 Planning, 7 Water Sciences, 3 Urban Design, 9 Ecology and 5 Other).

Over the period of a few weeks, each expert involved in the experiment sat individually with a researcher for an hour with the task of rating each of the four scenarios using a set of sustainability indicators. To accomplish this task, they were presented with documentation explaining each scenario and the visualisation media. A researcher guided the participant through each different type of media using a laptop computer and acted as a facilitator for working with the media. For each scenario, each media type was shown in order starting with 2D plans, photomontage, 3D recorded video, an aerial view of the interactive 3D mode and then finally an interactive eye-level walkthrough of the design. The interactive walk-through operated using a video game style controller and the ability to "fly" off the ground was available. No participant actively operated the laptop. Instead, the researcher would control the media on the command of the participant. For example, with the interactive 3D walk-through, the researcher would move around based on the verbal commands of the participant. This was done to avoid varying levels of computer literacy or confidence affecting the overall results. Some participants had prior knowledge of the area involved, but some did not.

After a participant viewed the scenarios, they were asked to score the scenarios based on the sustainability criteria. As part of this questionnaire, they were also then asked a series of questions about their usage of the visualisation media (see Appendix A for a copy of the questionnaire).

The questions were designed to elicit the amount of exposure each participant had to the types of media in the experiment and the rating given to each media type for understanding the scenarios using a 7 point Likert scale [72].

Given the ubiquitous nature of 2D plans and mapping data for landscape scenarios, an attempt was made to identify how much each other form of available visualisation media added to the information conveyed in the plans using a 7 point Likert scale. Finally, the participant was asked their preference for having a full screen 3D visualisation with no surrounding user interface or just viewing the 3D model in a designer window.

In addition to this, a plugin to Simmetry 3d was written that recorded the position, direction and up vector of the camera in the eye level walk-through every second, so that the movement of participants in the scenarios could be tracked. Each time the interactive walk-through was completed, a file would be created that held the data and a manual log was kept to maintain a list of actual participant movements in order to separate out any trial or setup runs.

3.2.2 Results

The questionnaire was completed by 32 people, which represents a small, but at least indicative sample. Considering the previous exposure of participants to the media types, there was a significant trend towards more traditional media rather than the interactive 3D visualisations as can be seen in Figure 9. It is interesting that walk-through videos remain uncommon despite the technological barriers to production being lowered in the last few years. It is likely that, as walk-through videos may require a 3D model to be produced, this is why they remain less often produced for landscape proposals.

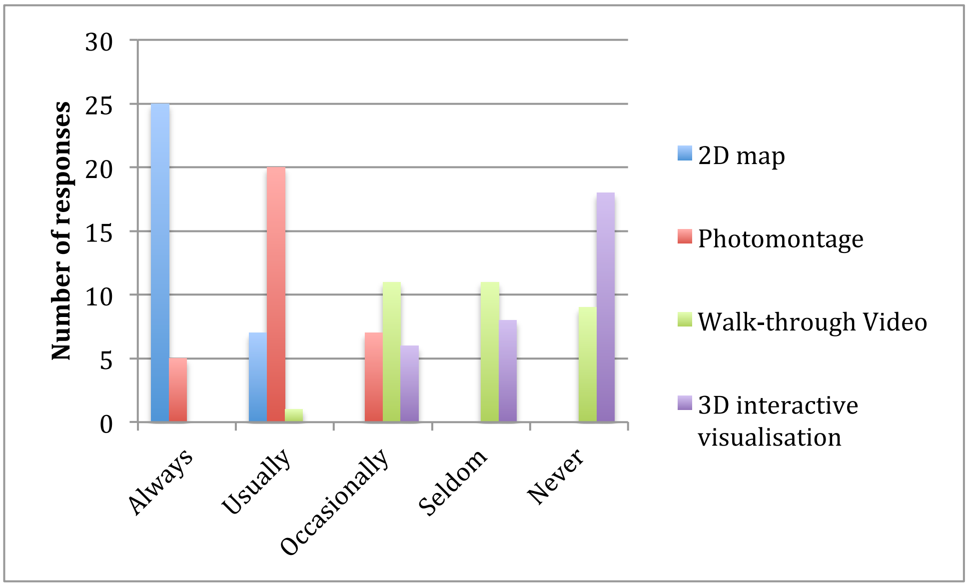

Figure 9 - Familiarity with the visualisation types available

It can be seen in Figure 10 that there is a significant trend to rating all media types towards the more preferable end of the scale, but that the 2D map and interactive 3D visualisations are most highly rated by the participants. The outlying lowest rating of the interactive 3D visualisation was by a participant who noticed that an error in translation from plan to 3D model had occurred and therefore judged the quality of implementation, not the media type itself.

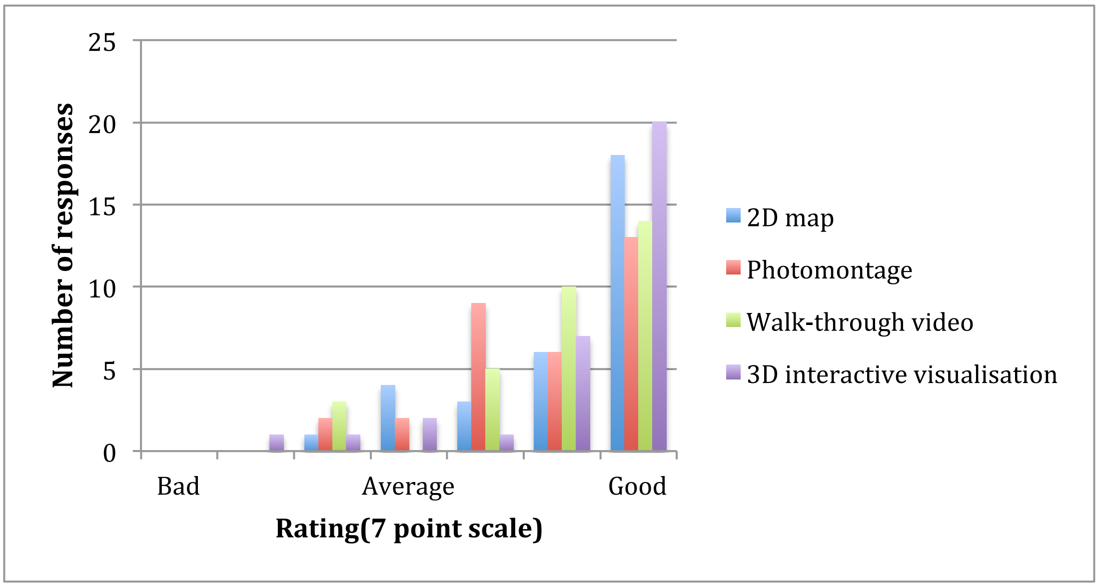

Figure 10 - Ratings of the suitability for each visualisation type for aiding understanding of the scenarios

Figure 11 shows the results of the rating of the extra information provided by the different types of visualisation media on top of the information already conveyed by the available plans. It shows a strong result to the interactive 3D visualisations as the type of media that can provide the most extra information. This result is in accordance with previous research results that suggest interactivity in visualisation is highly rated [30, p. 187].

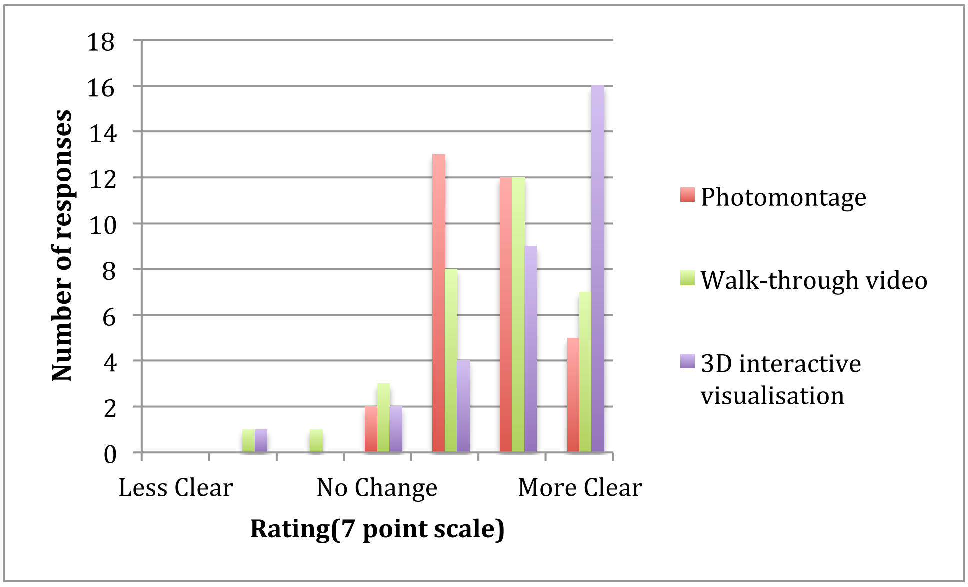

Figure 11 - Ratings of the extra information imparted compared to just using the maps provided

Both videos and the interactive 3D visualisation were available in full screen or in windowed mode on the computer. It can be seen in Figure 12 there is an overall preference for full-screen visualisations to windowed ones, but it seems that the choice is irrelevant to a significant section of the sample. It is probably necessary to run further studies to clarify the situation further.

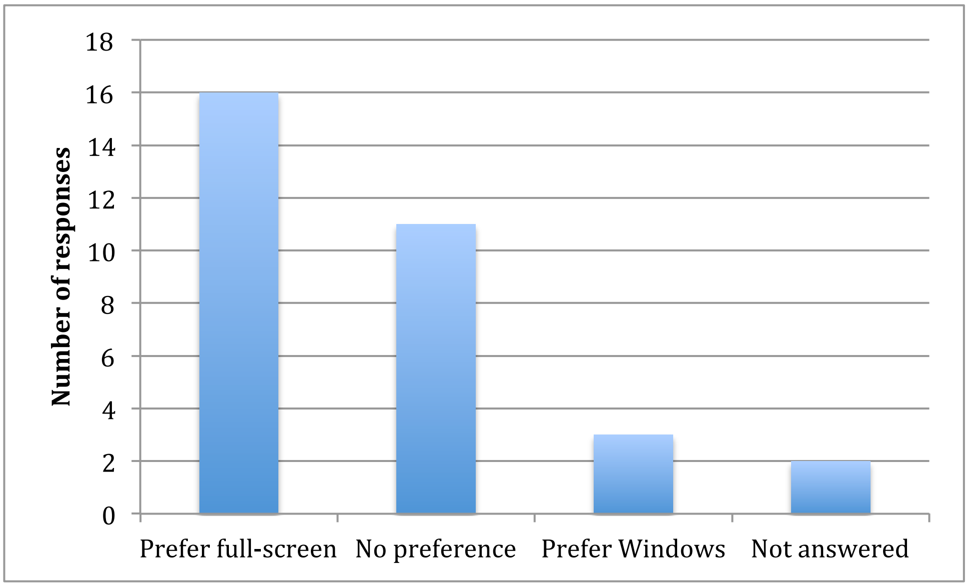

Figure 12 - Preference for full screen to windowed interface for interactive 3D visualisations

The automated tracking system plugin collected a set of files, which held the data that defined the movement paths within the Simmetry 3d model for each participant. The data was visualised in two ways. Firstly, each journey was re-imported into Simmetry 3d using a custom importer as a linear path, which could be overlaid on the 3D model, or over a 2D top down render of the 3D model. This was useful to see how the participants moved through the model. However, this style of visualisation did not communicate well if a person remained in one position for a while.

The VU-FLOW system [71] overcame this problem by visualising time-spent within each grid square of its 2D map. Hence, another exporter was written that took the position data and converted these from model co-ordinates to grid co-ordinates. The resolution of each grid square was 1m x 1m and each grid point held an integer value that would be incremented for each point sample that fell upon it. A separate grid was created for each scenario. These grids were then imported into ESRI ArcMap and the “Raster to point” GIS function applied to them. This process results in point based GIS vector files that have the grid count value associated with each point. This vector data can then be used as an input to the “Kernel Density” GIS function (Search Radius: 26.6333, Area Units: Square Map, Output Cell Size: 3.196) that converts the points to a raster surface holding an estimated density of the point data. The resultant grid for each scenario was then converted to a colour relief bitmap and was re-imported into Simmetry 3d and blended with a grey-scaled 2D top down view of the scenario. The results of the density function for the flood channel scenario are shown on the left in Figure 13 and with the movement paths overlaid on the right.

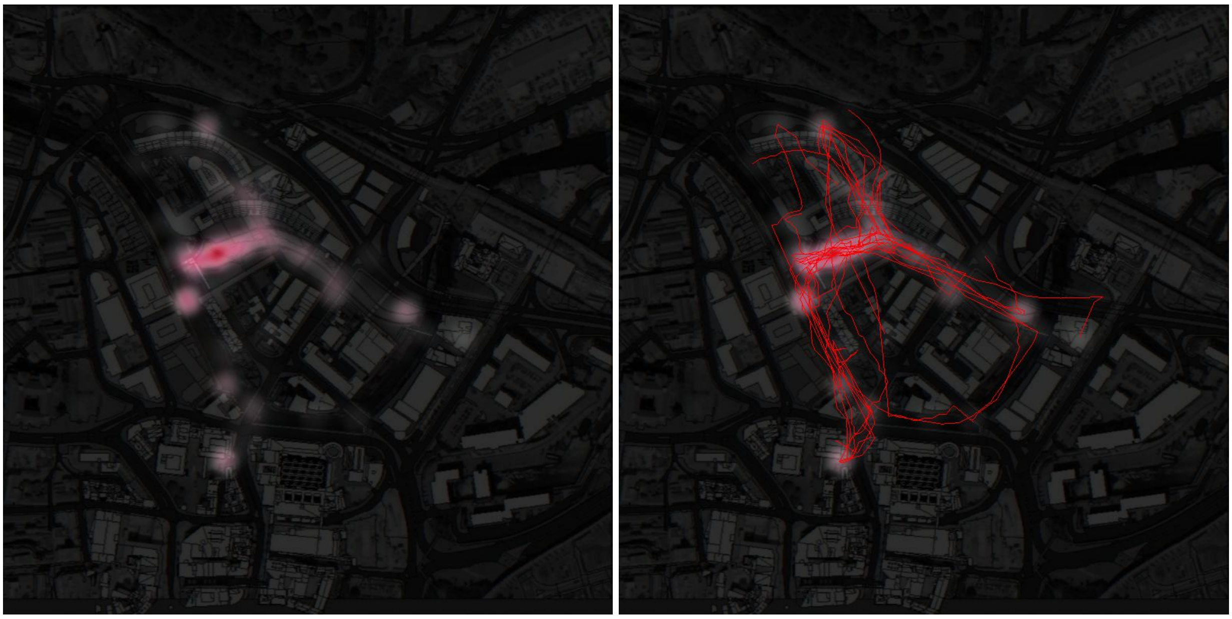

Figure 13 – Density function (left) and density function and movement tracks (right) for the flood channel scenario

It is interesting to note that although there was the possibility to move anywhere in the map, including flying from point to point, the movement of the participants seems mainly analogous to the pedestrian access in the scenario.

Figure 14 shows the resulting images produced for all four scenarios. The walk-throughs all had the same starting point in the lower left area of the map, which is clearly visible in the results. The task of interpreting the meaning of the results for those scenarios is left to better qualified people. Nevertheless, it is important to note that, by employing this presence tracking methodology, a designer can gain feedback into perceptions and "hotspots" of their designs.

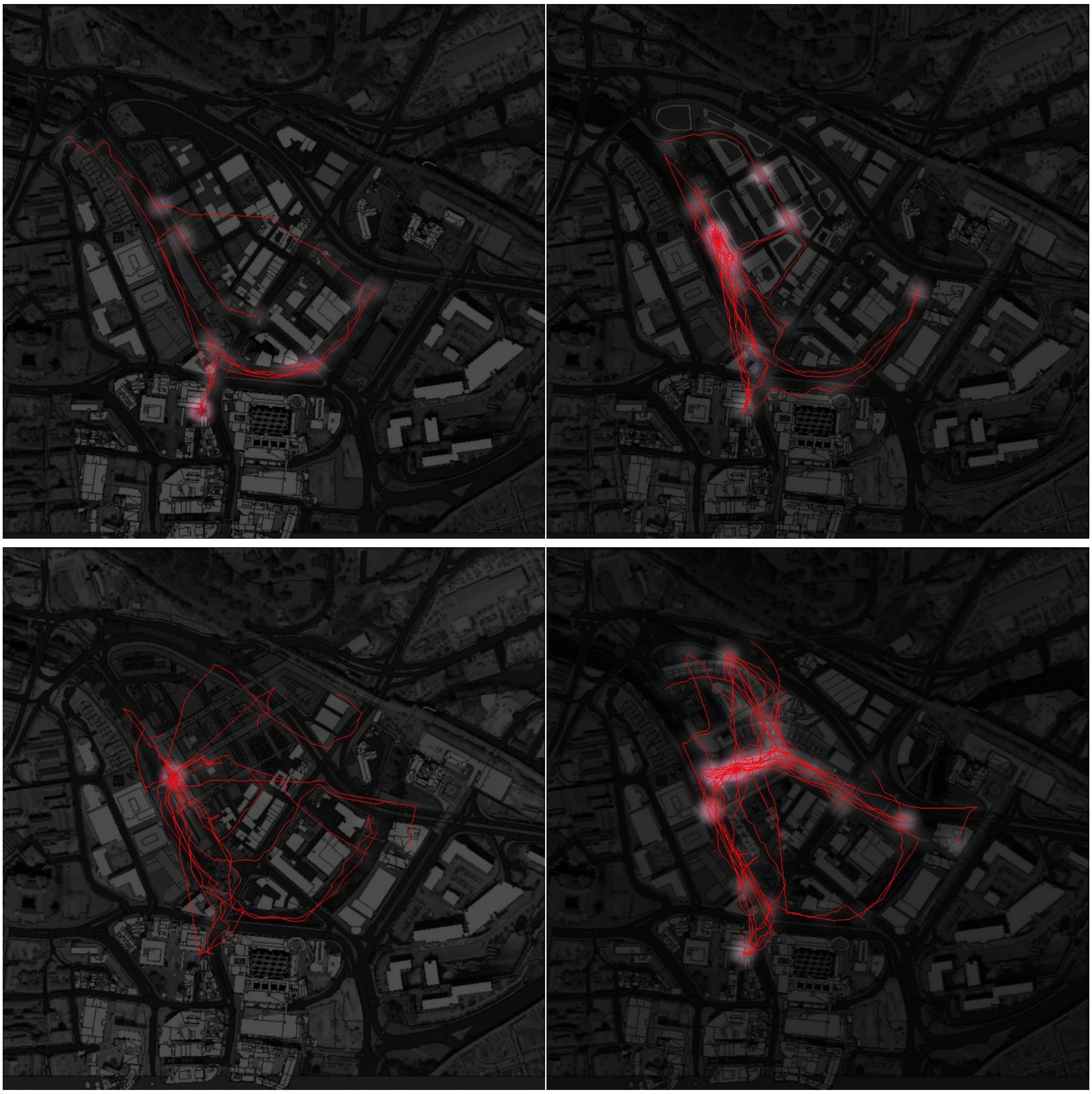

Figure 14 – Density and movement tracks for (clockwise from left) status quo, local council regeneration, hard urban and flood relief channel

Regarding the results, the study confirms the ranking of interactive 3D visualisations over videos and photomontages and these results occur without previous exposure to the technology. However, it is worth noting the high rating of 2D plans by the experts even with the 3D visualisations available.

Previous research and this study rely heavily on self-reporting, which is a practical approach to judging the value of visualisation media to a user, but it is not the only method. The next experiment follows the work detailed here by capturing actual usage of visualisation media.

3.3 MEDIA CHOICE EXPERIMENT 2

The aim of this section is to report on the results of an experiment run to discover how participants of a collaborative planning workshop use different media, both traditional and interactive 3D, all detailing the same future scenario. It presents a novel methodology using video capture to gather data on the usage of visualisation media.

3.3.1 METHODOLOGY

An experiment was conceived that would present several types of visualisation media to the participants in a planning workshop, including interactive 3D models. The duration of usage of each media type has been recorded and analysed. Participants were subsequently asked to rank the media types in order of suitability for aiding discussion so that these results could be compared with observational data. This section details the experimental set up, how the different types of media were created and the time taken to do this, the data collected and the analytical procedure used on the data.

3.3.2 EXPERIMENTAL SET UP

The Sheffield Waterways Strategy Group (SWSG) is a loose collaboration of professionals and members of the public with interests in the rivers of Sheffield. As part of a larger research project, URSULA[12], members of the group agreed to a series of collaborative workshops connected to redesigning an urban river corridor. The first of these sessions was convened to expose SWSG members to interactive 3D visualisation technology in an attempt to remove any novelty value.

In order to answer the research question detailed in the Section 3.1, that is whether *participants within a small participatory group setting will prefer to use interactive 3D visualisations of a site*

[12] http://www.ursula.ac.uk

scale proposal over more traditional methods for communicating proposals, a second workshop was convened with members of the SWSG for research purposes that would examine a real planning proposal for a site in the urban centre of Sheffield. The site chosen for discussion is one that suffered a recent major flooding event in 2007 and is also part of a redevelopment area targeted by the city council. Therefore, the council proposal detailed a flood defence scheme that incorporated a riverside “pocket park”.

The overall workshop was split into several separate sections. Firstly, a member of the council presented the proposal and the larger context of flood defence that it sits within, so that all members of the SWSG present were fully aware of the content of the proposal. The experimental session, which lasted 50 minutes, was conducted subsequently and this, in turn, was followed by a final session where the participants were able to comment about a wider range of future scenarios than just the council proposal.

There were a total of 11 participants in the workshop, six members of the SWSG and five researchers present, one of whom facilitated usage of the computer system. One member chaired the meeting; one controlled the cameras whilst the others were there as observers for other independent research objectives.

The SWSG participants in the experimental session were invited to discuss the council proposal and a range of media were provided by the researchers to support this, as shown in Table 1. The media were all based on the council proposal or existing mapping data of the area and were designed to have a similar appearance. The media types were selected to capture both “traditional” forms of communication of proposals (see Figure 15 to Figure 18) and the more recent interactive 3D methods that could be provided in the time available for preparation of the workshop.

It is useful to understand the software tools available for presenting models for interactive 3D modelling. There are two types of software prevalent for displaying interactive 3D visualisations suitable for a examining a site scale planning workshop:

(i) 3D CAD, GIS or modelling packages that provide a visualization of the site (example shown in Figure 19)

(ii) first person walk-throughs that provide a full screen 3D visualization of the site(see Figure 20)

In the first category sit a variety of software solutions that exist to allow the construction and view of arbitrary 3D geometry from two backgrounds: Computer Aided Design software, such as AutoCAD, and 3D modelling packages used for high end rendering solutions, for example Maya[13] and 3D Studio Max[14]. However, increasingly the line between these software tools is being blurred by software packages, such as SketchUp[15], which provides CAD style design with generic 3D modelling. In addition to these, there is 3D GIS, which is essentially a standard Geographic Information System with the functionality to represent a 3D view of the 2D geographic data store alongside different views of relational data held in the system. The view of the 3D model in these forms of visualisation is normally controlled by a mouse and keyboard combination utilising a menu and icon driven user interface, although other controllers able to manipulate the 3D view are becoming available.

Computer video game technology allows users to experience a landscape model at eye-level without the distraction of a GUI surrounding the image. They provide an immersive, easy to understand method for displaying a 3D visualisation, allow a different method of control via standard video game controllers and can be displayed in stereoscopic 3D to provide a greater feeling of depth to the scene.

The media chosen for the experiment were to be representative of two styles of interactive 3D visualisations: menu and icon based, and eye-level walkthroughs. The eye-level walkthrough was also to provide stereoscopic output as an option for the participants to choose. The different types of media were placed closely together and within easy reach and participants stood for the duration of the experimental session. The lack of chairs was a deliberate choice for the experiment to ensure that there was a low barrier to movement between available media types as can be seen in Figure 21.

The experiment was held in the Reflex studio[16], the Virtual Reality laboratory at the University of Sheffield that allows groups of people to interact with virtual environments. It consists of a single

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[13] http://usa.autodesk.com/maya/

[14] http://usa.autodesk.com/3ds-max/

[15] http://www.sketchup.com

[16] http://www.shef.ac.uk/reflex/

room with a backlit 3m x 2.5m (10ft by 8ft) screen that is connected to a computer that can run interactive 3D visualisations, using a quad-buffered graphics card that allows the output of stereo imagery from the 3D visualisations, viewable using synchronised shutter glasses. Figure 22 illustrates the layout of the screen, tables and display boards used to present the media and positioning used in the experiment for each media type can be found in the final column of Table 1.

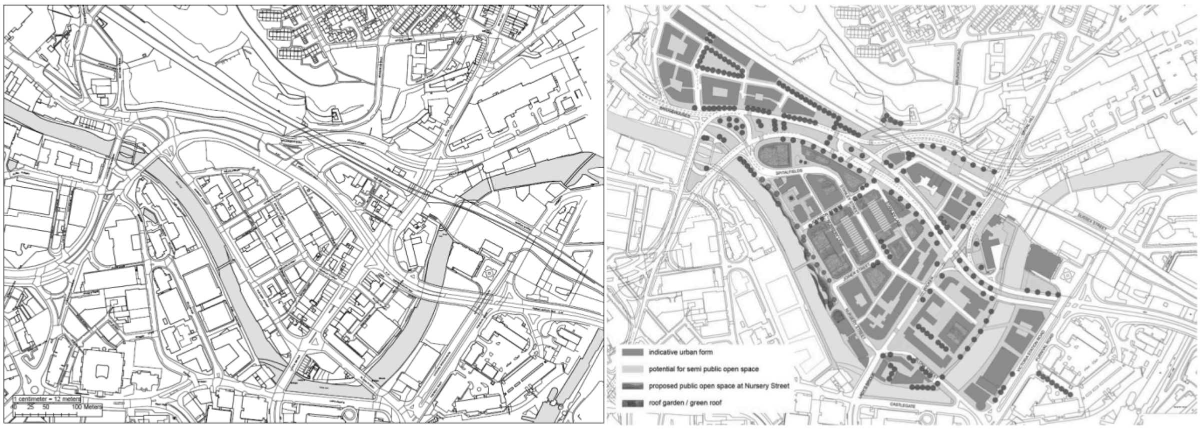

Figure 15 - 1000 scale map © Crown Copyright/Digimap 2008 and council master plan for the proposal area and context

Figure 16 - 1:1000 scale top down view of the proposal

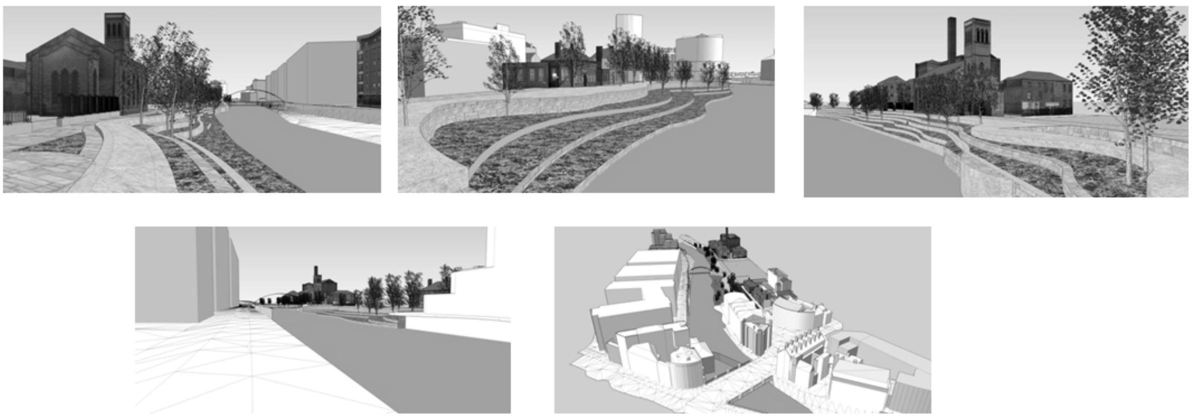

Figure 17 - A3 views of proposal

Figure 18 - 1:500 scale physical model

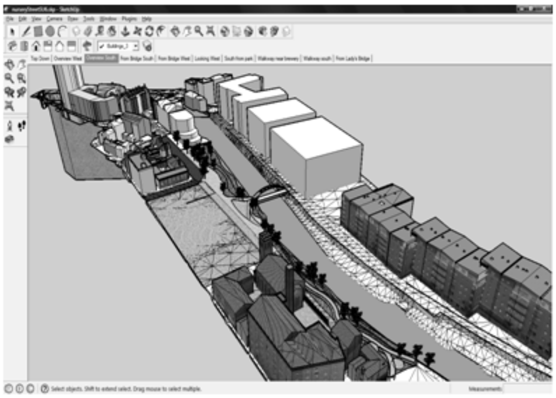

Figure 19 - 3D SketchUp “3D CAD style” program

Figure 20 - Walkabout 3d walk-through, video game style controller and 3D glasses

Figure 21 - Experimental set-up

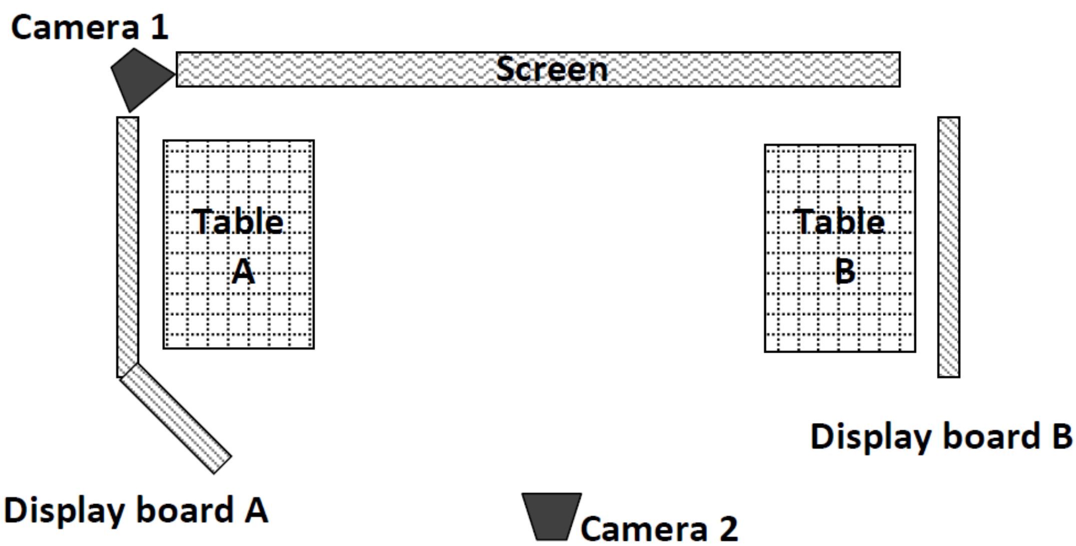

Figure 22 - Diagram of layout of media and cameras (not to scale)

Media	Type	Position
A1 1:1000 scale plan view	Traditional	Display board A
5 x A3 image views	Traditional	Display board A
1:500 scale model	Traditional	Table A
3D CAD (SketchUp)	Interactive 3D	Screen
3D walk-through with game controller	Interactive 3D	Screen
3D walk-through with game controller and stereo glasses	Interactive 3D	Screen
A1 1:1000 scale current situation map	Traditional	Display board B
A1 1:1000 scale Sheffield Council “master plan” plan view	Traditional	Table B

Table 1 - Types and categorisation of media by current usage

3.3.3 *Creation of media types*

Firstly, a 1:1000 scale map of the existing area with street names was created detailing the same area as a Sheffield City Council master plan that included the discussed proposal (see Figure 15). This was prepared from UK Ordnance Survey map data using ArcMap and coloured in a similar style to the other media types. This process took around three hours to acquire, prepare and print both the map and the master plan.

To create the other media types, an area master plan view and a SketchUp reference model was donated by Sheffield City Council. The SketchUp file contained a detailed view of just the area around the proposed new riverside park. Care was taken to ensure that all the media types produced contained similar visual styles.

The 3D reference model was built manually and took approximately 7 hours to construct from an existing base topography, but it is unknown how long the master plan took to construct. From the 3D model, several different views of the pocket park proposal were printed out, including the A1 1:1000 scale plan view (Figure 16) and five A3 views (Figure 17) which were created from different positions showing aspects of the proposal, from both bird's eye and eye level. These took around 1.5 hours to select, prepare and print out.

The 1:500 scale physical model (Figure 18) was commissioned to be created as an exact representation of the reference mode and took 60 hours to build. The 3D CAD model used was the unchanged reference model run in SketchUp (Figure 19) and this also became the basis for the walk-through model using software which allows for a computer game style walk-through, called Walkabout 3d[17] that has native support for SketchUp models. This software supports a video game controller human-computer interface that allowed the participants to move around the model at eye level. This software can be triggered to run normally or in 3D stereo via an option in the user settings (Figure 20).

[17] http://www.walkabout3d.com

3.3.4 DATA CAPTURE

At the beginning of the experiment, each media type was introduced to the participants by a researcher. Whilst the traditional media types were available in physical locations around the screen, the interactive 3D media were all made available as separate windows on the screen, so that participants were able to pick them should they wish. The participants were able to choose to navigate the digital models themselves, or have a facilitator navigate for them. Having been given permission by the participants to record, the entire workshop was recorded with two Digital Video cameras, which were positioned in the room to maximise the capture of the usage of the different media types. The participants were then left to discuss the proposal between themselves with the researchers remaining in the room, but not part of the discussion.

After the allotted time had elapsed, the discussion was brought to an end and a questionnaire was distributed to each participant. This asked them to record their familiarity with the usage of each media type for communicating planning proposals. It also asked them to rank media categories in order of suitability for both aiding their understanding and facilitating their discussions of the proposal. The categories selected were as follows:

- Paper plan
- Physical model
- Printed 3D perspectives
- 3D visualisation (e.g. Sketchup)
- 3D walkthrough with game controller
- 3D walkthrough with game controller and glasses

This categorisation grouped the proposal 2D top down plan, the Council master plan and the map into one category of media "paper plan" as these media types were determined to be offering similar information to participants and to reduce complexity understanding the questionnaire. This form of self-reporting question is used to gather data about visualisations [17][53] and it was deemed of interest to examine how each media type was ranked and the actual usage of that media type in discussion.

3.3.5 *ANALYTICAL METHODOLOGY*

Post workshop, the videos of the experiment were analysed to capture the usage of each type of media by the participants. It was considered necessary to form a set of criteria that defined usage of a media type. After initially watching the videos to determine a suitable methodology, these were defined as one of two physical actions towards a particular media:

- Gesture based "point at"
- Identifiable head position "look at"

This scheme is similar to that of Lewis and Sheppard [56], who identified gestures indicating interest in different images, but which were recorded via session notes, not video. In addition to the gesture based system, the video audio recording was also used to support gesture identification so that a "*point at*" gesture could be distinguished correctly from a simple gesticulation. As an example, both a "*point at*" gesture and "*look at*" gestures can be seen in Figure 4, which is a frame of video from the session showing the participants using the interactive 3D walk-through media.

Figure 23 - Frame of video showing the participants looking at one media type

The analysis of media type usage took place using NVivo 8[18] software that allows for periods of time in videos to be assigned against different user defined codes. Each media type was given a code and

[18] http://www.qsrinternational.com/products_nvivo.aspx

then as usage of a particular media type was identified, that section of the time line of the video was assigned against the appropriate code. This allows the whole video timeline to be broken up into usage of the media types and results in the timed usage of each media type. Throughout the session all participants took turns in speaking and used different media to support their discussions. Generally, this kept the attention of the group fixed upon a particular media or the person speaking. However, occasionally in the session an individual participant referenced a media type whilst the rest of the group was otherwise engaged to establish total usage. So, in this case if two participants used more than one media at once, both usages were coded into the timeline. The facility in the software that allows reduced play speed was essential to the process and aided the accuracy of timing the usage. For simplicity in viewing the results, only one of the two video tracks was encoded, but the second video was used to check all the participant's movements, if the first view was blocked. Although the camera tracks were started at slightly different times, the time differential between recordings was calculated by identification of a reference event that occurred at the beginning of both the videos. This offset then allowed the transfer of events seen only in the second video back to the first timeline.

Media	Category
A1 1:1000 scale plan view	2D plan
5 x A3 image views	Images
1:500 scale model	Physical model
3D CAD(Google Sketchup)	3D CAD
3D walk-through with game controller	3D WT
3D walk-through with game controller and stereo glasses	3D WT Glasses
A1 1:1000 scale current situation map	Overview plan
A1 1:1000 scale Sheffield Council "master plan" plan view	Overview plan

Table 2 - Coding categories

The timeline was coded with the categories as shown in Table 2. Both the current situation map and master plan map were coded together as these were seen as two examples of one media type. The 1:1000 scale plan was separated in the coding process as this contained less contextual information than the overview plans.

3.3.6 RESULTS

This section presents the results obtained from the coding methodology described in the previous section, the questionnaire and the comparison of the two.

Media Type	Usage(min:second)
Overview Plan	14:18
3D WT	07:37
3D WT Glasses	05:53
3D CAD	01:47
Physical Model	01:17
Images	00:15
2D Plan	00:14
Total	31:21

Table 3 - Media types and duration of usage

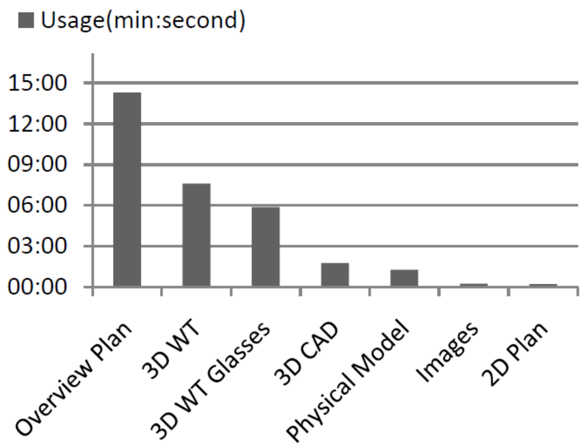

Figure 24 - Media types against usage

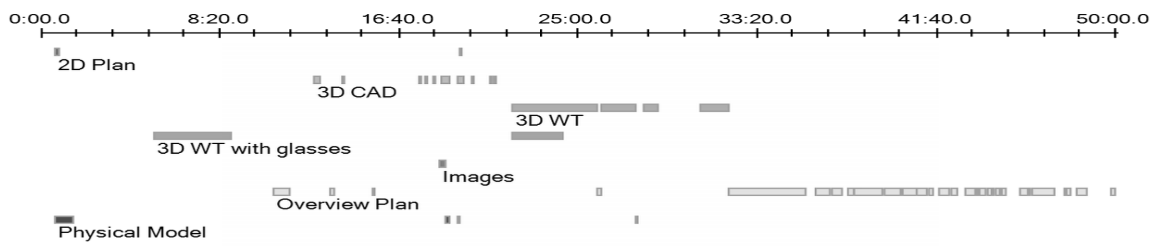

Figure 25 - Usage of media types

With reference to the coded timeline, shown in Figure 25, discussion referencing the media types occurred for large parts of the workshop. It can be clearly seen, in Table 3 and Figure 24, that overall the most popular media type used was the traditional paper overview plans, but not the 2D plan of just the proposal. The 3D walk-through without 3D stereo was then chosen in preference to the 3D stereo view of the walk-through. The 3D CAD was briefly used to support a period of discussion, but the images, physical model and 2D plan were referenced by participants, but hardly resorted to.

The timeline also demonstrates that media types were largely used in "blocks" with one type supporting the discussion for periods of time before swapping to another type. Very little multiple referencing of media types occurred within the workshop, mainly people choosing to wear their 3D glasses or not.

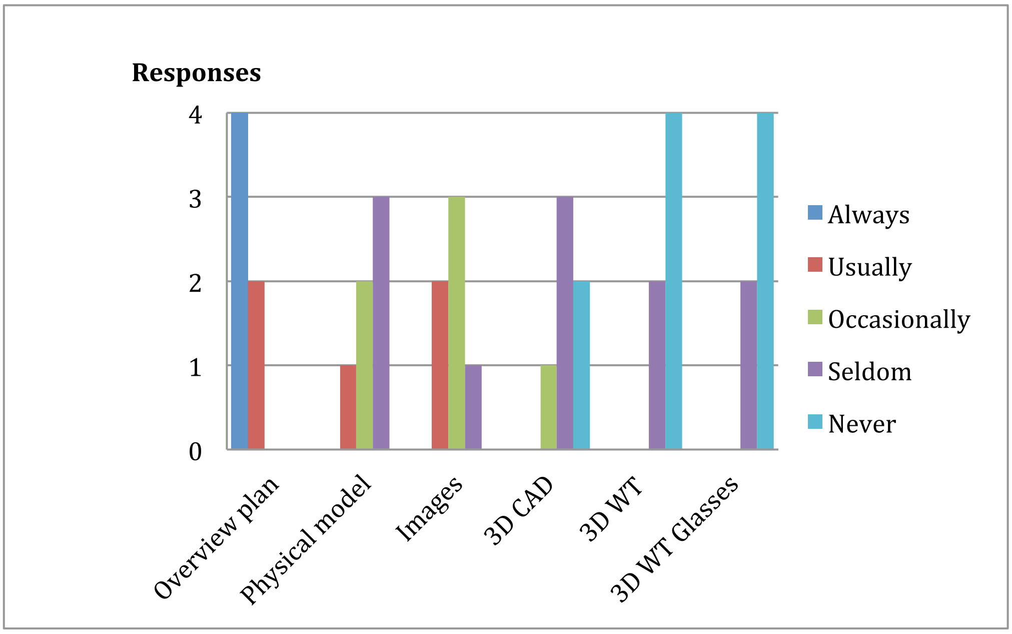

Figure 26 - Participant familiarity with each media type usage for planning proposals

Examining the questionnaire data, it can be seen in Figure 26 that the familiarity of the participants with the various media types supporting planning proposals shows the same trend, as found in the previous experiment, of commonly encountering the traditional media types, but far less exposure to the interactive 3D media types used in the experiment.

The participants were asked to individually rank each media type for the "suitability for aiding your discussions with other participants of this workshop", where 1 was most suitable and 6 was least suitable. Figure 27 shows two of the charts for the relative frequency of responses per rank against the actual observed usage for overview plans and 3D walk-throughs with game controller. There can be seen a wide variance in how the users ranked the various media in terms of their suitability for supporting discussion with the overview plan being at the opposite end of the ranking scheme, but a good correlation for the 3D walk-through with game controller.

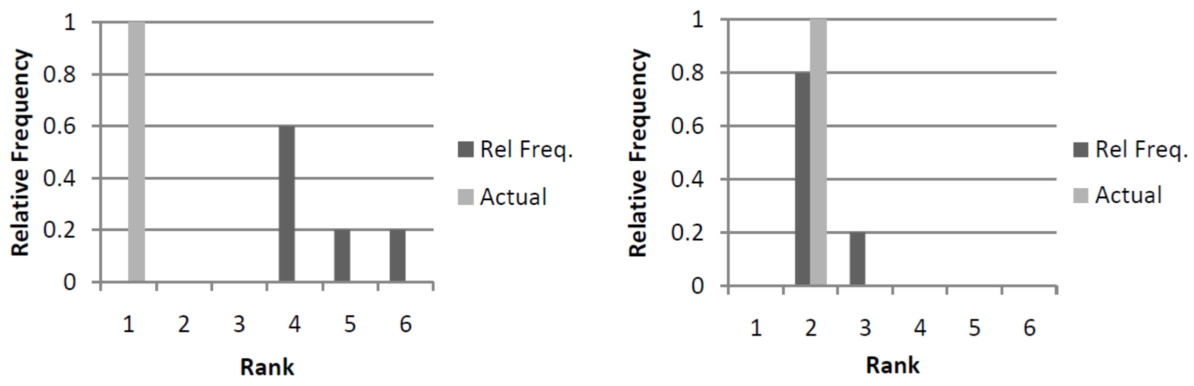

Figure 27 - Relative Frequency of rankings assigned by participants and actual usage of overview maps and 3D walk-through with game controller

Calculating the Spearman's rank co-efficient for all rankings of media types against observed usage (*ρ = 0.5691*) suggests a weak correlation. However, the sample size is too small to draw conclusions from and further data needs to be collected to understand this area more fully.

This section has outlined a method of collecting observational data on the usage of different media types within a collaborative planning workshop. Regarding the coding process, it could be argued that the methodology involved in categorisation of the different media types is, despite best efforts, subjective. This could potentially be mitigated by a second person also coding the video timeline and averaging the results. However, it is worth noting that the coding of the video timeline was an involved and time consuming process, which required multiple passes through the video and days of work before results could be finalised, even for a single 50 minute period, and therefore would require significant resources to code with multiple people.

The most used media type was the mapping containing a larger context, which may have been connected to the fact that the proposal related to flood defence; a problem that is not limited to site scale. However, this can be seen as evidence that isolated areas of visualisation are not as useful as ones which contain contextual spatial information. From the time line analysis, it is clear that the participants preferred to focus mainly on one type of media at a time to support their discussions, although this focus would change. It is important to note that all media types were used by the participants, but that the usage of the 2D plans and interactive 3D visualisations predominated, despite the lack of previous exposure to this technology.

When analysing the construction time of a physical model in comparison to the actual usage for this study, it can be seen that this media type was almost redundant, given the access to interactive 3D visualisations. It can also be seen that when an interactive 3D model is constructed then it may not be necessary to provide still images. However, it is interesting to note that should time be taken to develop an interactive 3D model, then it is relatively time efficient to then produce 3D views from this if they are required.

Comparing the questionnaire results to the actual usage results also raises interesting discrepancies between the actual usage of media and participants' perceptions of the suitability of that media for discussion. It is very likely that the rating of suitability for aiding discussion and time used measures are not directly comparable. Nevertheless, if this experiment had been performed with questionnaires alone, the actual usage of the plans may have been obscured. Therefore, researchers should perhaps be guarded against drawing too strongly on the results of self-reported rankings without observational data also being collected.

Finally, this is a study of a limited number of technical experts working as a group to discuss a small site level proposal and, as such, it is hard to form strong conclusions. However, the methodology presented is capable of providing quantitative data that can be analysed and it is hoped that it, or similar methods, could be used in other similar studies. It will be of interest to discover whether these results can be replicated and how different group sizes, or differing participant mixes (public/experts) may affect them.

3.4 DISCUSSION

In this chapter, a new methodology has been outlined that can be implemented alongside self-reporting techniques to facilitate the understanding of the usage of visualisation media. In addition, it has been shown that tracking of the movement of users within an interactive 3D visualisation is possible and that the resultant quantifiable data can be presented in the spatial context of the landscape design.

There is still much research to be conducted to fully understand the nature and role of interactive 3D visualisation techniques within the landscape design and public participatory processes and it is hoped that these methodologies can be adopted by researchers for future studies.

Regarding the results from the two experiments, the data does indicate that there is preference for and observable usage of both 2D plan and interactive 3D walk-throughs, which leads to the conclusion that providing both these types of media is a powerful combination to support discussion about planning proposals. Given these experiments were conducted with experts who are more likely to be familiar with mapping than perhaps most of the general populace is, then further work should be undertaken to identify what the choice of the public is for visualisations media. However, if experts who are used to seeing landscape scenarios in plan form rated interactive 3D visualisations as providing the highest form of extra information then it is likely this would hold true for the general public.

It is also apparent from the results that the participants prefer the use of video game “first person” views with minimal user interface present to a 3D CAD style interface. This suggests that software tools written to support participatory design by experts should be able to either simultaneously display both mapping and a 3D walk-through mode, or have the facility to switch between these views rapidly.

Chapter 4

3D LIM THEORY

This chapter presents a theoretical framework for the construction of a 3D LIM that combines real-time graphics, landscape design and analysis of landscape performance for site-based design. Section 4.1 discusses the current nature of landscape design practice using 3D visualisations. Then, Section 4.2 defines a 3D LIM, proposes key functionality that this would provide and also explores how a 3D LIM would perform landscape performance assessment. Finally, the position a 3D LIM could take within the landscape design process is presented in Section 4.3.

4.1 Current Design Practice

To understand why a 3D LIM may be a useful tool in landscape design, it is necessary firstly to consider the current practices used in landscape design, specifically relating to 3D landscape models.

Regarding site-based landscape design using real-time 3D graphics, there seems to be several barriers to their role within this process. Firstly is the expense, in terms of time and financial resource, involved in constructing an interactive 3D model of any given design proposal. Secondly is that, once a 3D model has been constructed, there are limited options for re-use and dissemination of the information contained within that model. Often specialised computer hardware is needed to display a model, such as the 13 projectors and 13 computers of the UFZ-Helmholtz Center for Environmental Research lab [73] meaning that people must come to the model and not vice versa. Even if the model can be displayed on a projector at a public meeting, the interactivity with the model is reduced as the number of participants increases. Finally, the use of real-time 3D graphics in landscape design is usually limited to one of visualisation. This can mean a lot of effort for only small return. Figure 28 highlights how the use of 3D models in landscape design typically takes a very linear path. A designer creates a design in sketch or CAD/GIS form and either they, or another member of the design team, then constructs a 3D model based on the information in the plan.

This 3D model is then used to create visualisations of the design to help inform (or persuade perhaps?) whoever is involved in the decision-making process that will finally approve or reject that design.

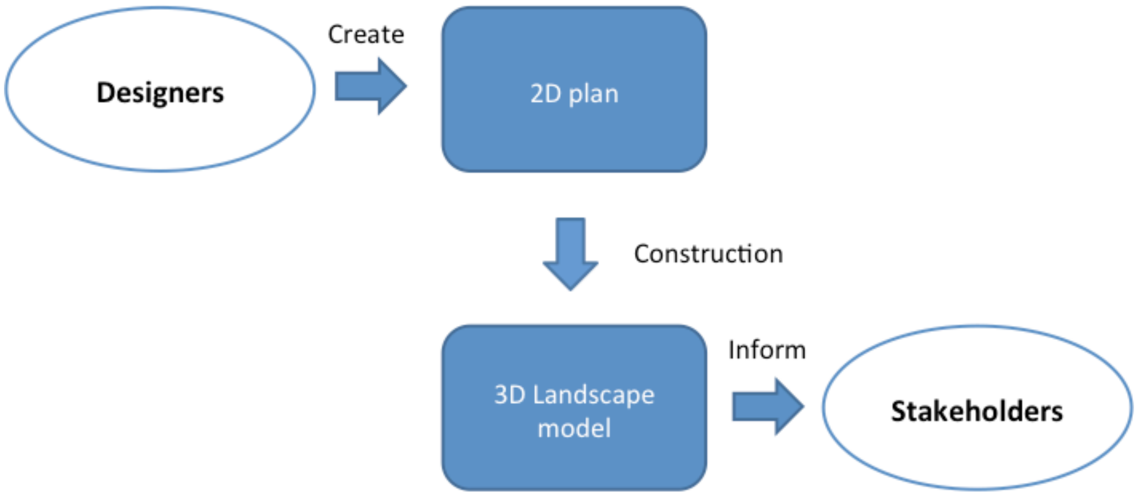

Figure 28 – Traditional use of 3D graphics for a landscape design

Employing this methodology means often only a handful of finalized designs reach the stakeholder. This state of affairs may or may not be acceptable, especially if a policy goal of increased public participation is required.

Revisiting the original Steinitz theory of Landscape Change [26] also defines a clearly linear design path, following three passes through the modelling process to come to a definitive answer. The first pass shapes the scale and requirements for the modelling process, the second defines how the modelling will take place and the final pass is when the modelling takes place. Therefore, Steinitz defines a linear multi-model system from which, once results of the modelling stages have been completed, a design solution can be achieved.

An issue with the Steinitz framework arises, however. Although it defines a clear set of stages, it makes the assumption that the designers and stakeholders involved are able to, at the outset, completely define the problem at hand. It also assumes a perfect implementation at all stages, whereas an actual design process may be a more flawed version of this. A design team does not always have the perfect knowledge that allows them to specify the problem at the beginning of the design process. In fact, it is often the design process itself that reveals components to be added to the initial design brief as the problem becomes clearer to everyone involved. For example, when a 3D landscape model is formed from a 2D plan, it might raise issues that the original designer had not envisaged. This would create feedback loops between the various stages of modelling in the Steinitz framework.

The Steinitz model has clear parallels with the largely questioned classical waterfall model of software design proposed by Royce [74]. This prescribes a top-down approach to software design, which also struggles with the same problem of perfect knowledge of the design goal at the outset. A contrasting solution to software design is that of Agile programming [75]. This identifies that often requirements will alter over time and that it is better to produce working solutions in an iterative manner. It is the iterative nature of this Agile design process that could be of interest to landscape designers and stakeholders. Indeed, Steinitz has a feedback loop added at the end of the three passes that acknowledges the iterative nature of designs. Software that supports the landscape design process should acknowledge the Steinitz stages but also cater for the iterative nature of design within and between Steinitz stages.

Landscape designers often create multiple outputs for a landscape design process: plans and mapping; static 3D imagery, sketches and documentation. To make them as useful as possible software tools aimed at landscape design should support these output types. At the moment, this is not commonly the case. Plans and maps are generally constructed from GIS software and then often a separate 3D model is created in separate software, meaning that the 3D visualisation and the design can easily become unsynchronised as design alterations are made.

4.2 DEFINITION OF A 3D LIM

So, instead of leaving 3D modelling to the end of the landscape design process, it is suggested that it be made central to the design process. A 3D LIM would provide a 3D model of the current landscape as a starting point for the design process. In other words, instead of an end result of fixed 3D visualisations, it would become possible to interactively edit a landscape model and visualise the results in real-time throughout the design process.

Clearly, any software tool that aims to support the landscape design process should accommodate as many of the models defined by the Steinitz stages as possible. So, given the need for sustainable landscape management, the integrated model also should be able to inform the user as to the performance of a future landscape. To understand the effect of design changes, a 3D LIM should be able to compare landscape designs both spatially, but also in terms of performance. Given this linkage between design and analytical model, a 3D LIM will fit well at both the level of Representation Models and Change Models and at the Process and Impact stages too.

The ideal response time of any system would be to appear instantaneous to the user, but this might not always be possible, especially when dealing with a complex 3D model. Miller made an educated guess that responsiveness of a computer system in less than or equal to 0.1 seconds will be viewed as real-time. He suggests that with any response over two seconds there can be a detrimental effect on the train of thought of a user and any response time greater than ten seconds will severely impair problem solving tasks [76]. Goodman and Spence also found that there was a 50% increase in the time taken to solve a graphical problem using a CAD style system when the response time moved from 0.72 seconds to 1.49 seconds, although they do state the timings may be task specific [77]. So, to avoid becoming a barrier to the creativity of the designer, a 3D LIM will probably need to respond in less than one second to user input, but the optimal system response times will need to be ascertained once a 3D LIM is available to be tested.

A 3D LIM is defined as an interactive software tool that supports the landscape design process in both the construction and judgment of a landscape design via 3D landscape models.

A 3D LIM would allow construction and interactive editing of 3D landscape models by the user, but it goes beyond a normal modelling/visualisation software package by adding a semantic structure to all the elements in the modelled 3D landscape. This semantic structure behind the model would allow the software to predict landscape performance by creating the inputs to linked analytical simulations.

A 3D LIM will allow the creation of a range of visualisations of stored designs and simulations and will provide interactive eye level 3D walk-throughs as part of this range. In addition, the 3D LIM should be able to disseminate the data held in the system in as many ways as possible because this would facilitate participatory design and planning activities.

Landscape performance can only be predicted through the use of analytical models running simulations. An analytical model can be thought of as a “black box” in which inputs are entered and simulation results are output. A 3D LIM should be able to link to as many of these black box models as is required for the design process.

By creating 3D models that go beyond the normal geometrical description to hold further information about each element in that model, it is anticipated that a 3D LIM will be able to provide sufficient data to linked analytical models to perform analysis of the design with minimal user input. So, the extent of the semantic in the 3D model must be sufficient to supply all linked analyses with their required inputs.

There are two distinct categories for the linked analyses, real-time and offline analysis. The first category would include any models that are able to produce the results of a simulation in real-time or within a period where cognition of the results will not be impaired by the response time. However, detailed simulation of landscapes can often take a long time to run and these would fit into the offline category.

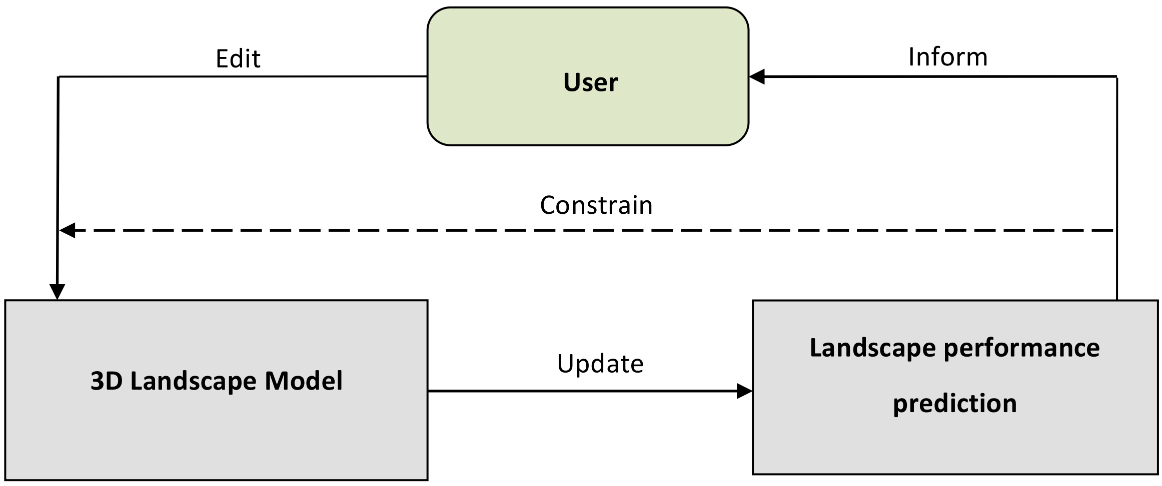

Figure 29 – Usage pattern of a 3D LIM

The real-time models could deliver both an immediate display of their results to the user and enable constraints to be placed on any manual alterations. This forms the "*Edit – Analyse – Inform – Constrain*" feedback cycle as shown in Figure 29. It is this feedback and constraint by linked analysis of design quality that helps improve the mental model of the designer. As a simple example, the system could update a display of the current cost breakdown of proposed planting schemes as the user alters the vegetation density. In addition, the user may be stopped from reducing the number of plants below a certain threshold, or from creating too many of a certain species based on cost, or planting guidelines.

However, it is not clear whether the constrain function may be too restrictive for designers to use as they may wish to break rules to construct designs that are transgressive. So, in other words, it would be possible for the 3D LIM to constrain, but the inform action of a 3D LIM may be a better way to communicate the breaking of a constraint.

It is anticipated that the results of both categories of linked analysis would be accessible in the 3D LIM both in the form of graphs, charts and figures, but also, where appropriate, visualised within the context of the 3D landscape model. This would give clear spatial context to any results and, as Wissen et al [78] proved this form of linkage between landscape visualisation and data can aid understanding of the data, whilst any importation process of simulation results into the 3D landscape model should be as automated as is possible.

Another important consideration of a 3D LIM would be controlling versions of designs, so that the user could make differential analyses between designs held in the system [79]. This would help a designer with the iterative nature of design and allow the 3D LIM to operate in the Steinitz Impact stage.

There are two clear advantages of tightly coupling black box analytical models to the designer's model. Firstly, it leads to a removal of any human error in translation of a proposal into two distinct systems, potentially by different people. Secondly, it increases the speed that alteration to designs can be analysed for performance.

4.3 USE OF A 3D LIM IN THE LANDSCAPE DESIGN PROCESS

Site-based design involves two sets of people: those who are generally experts in this field and who create a design, and those who judge the value of those designs. In a top-down planning process, these two sets of people may be one and the same, whereas in a more open process, it is likely there will be more people judging than designing. A 3D LIM should be a useful tool for both sets. An implementation of a 3D LIM should make landscape design more of an iterative process, as shown in Figure 30. The designer, or design team, can iteratively design as the system provides both visual and analytical feedback on their designs. In addition, the designers can use the visualisations and simulation results produced by the 3D LIM to instigate discussions with stakeholders, who can also then, in turn, influence the landscape proposals.

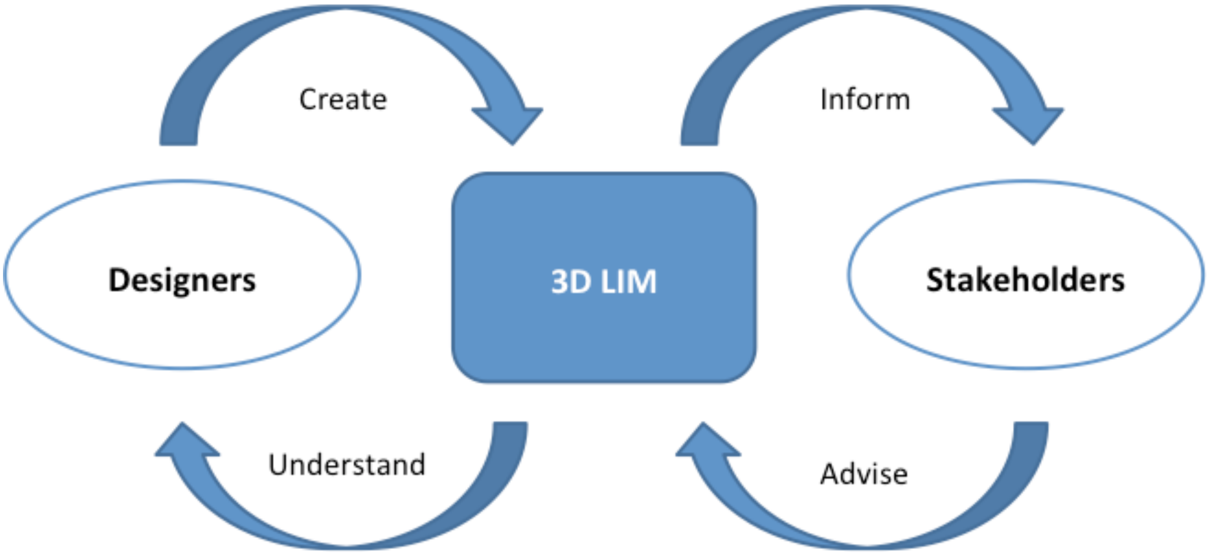

Figure 30 – User interactions with a 3D LIM

Given the promotion of the 3D modelling stage into the heart of the design process, the 3D LIM must address the problem of the time taken and complexity of construction of a 3D model, otherwise these barriers to adoption of real-time 3D graphics would be inherent in the adoption of a 3D LIM.

Finally, Batty [80] states that modelling takes place to explain, explore, experiment, and engage. The primary role of a 3D LIM is to provide a designer with a landscape modelling tool and a 3D LIM would seem well placed to support all the roles identified by Batty. The linked analyses combined with a 3D landscape model can aid explanation. The interactivity of the 3D views allows a user to explore and promotes engagement and, finally, the editable nature permits experimentation.

Chapter 5

IMPLEMENTATION OF A 3D LIM

The implementation of a fully functional 3D LIM as described in the previous chapter is not a trivial undertaking. Therefore, it was decided to construct a prototype that focused on proving it is possible to provide the key elements of a 3D LIM:

- Interactive construction and editing a landscape design
- Provision of an interactive 3D walk-through visualisation
- Analyses integrated with the landscape design
- Storage and comparison of multiple designs
- Dissemination of the design

This chapter will explore the implementation of a system to enable the construction and editing of a 3D landscape model, linking to a 3D visualisation and the storage of multiple designs.

There are many different types of models that could potentially be linked into a 3D LIM. The initial task was to integrate some form of analysis that could provide real-time feedback within and alongside the 3D model to prove it was feasible. This research is detailed in Section 5.4 and the other models that have been integrated into the system are detailed in further chapters. The different styles of analytical models that have been integrated into the 3D LIM prototype are detailed in Table 4.

Model	Type	Category	Chapter
Land usage	Geo-spatial analysis	Real-time	Chapter 5
Bayesian Network	Knowledge based	Real-time	Chapter 6
Micro-climate simulation	CPU intensive simulation	Offline	Chapter 7
Flood modelling	CPU intensive simulation	Offline	Chapter 7
GPU Pedestrian modelling	Agent based simulation	Offline	Chapter 8

Table 4 – List of different models linked to the 3D LIM

5.1 Interactive Construction and Editing

A primary goal for a 3D LIM is to reduce the amount of effort that goes into the construction of a 3D model. As mentioned before, procedural modelling utilises computational resources to construct a model. It has a history of successful use with landscape visualisation.

It has been used on individual elements of landscape models, from generation of realistic vegetation by Deussen et al. [81] to the construction of complex building models by Wonka et al. [22]. With the increasing prevalence of accurate mapping and elevation data, procedural modelling techniques for landscapes can be used to translate these rich sources of geographical information into 3D landscape models, thereby reducing the effort needed to construct such models. Hoinkes and Lange [21] developed a procedural modelling system that takes two dimensional GIS land usage data marked with "3D-able" attributes and produces a 3D landscape model. Procedural modelling has also been utilised in smaller scale landform design. Buchholz et al. [28] developed a system called "Smart Terrain", combining procedural modelling and categorised vector data to give the capability of procedurally generating a surface model by deriving and overriding heights taken from GIS terrain data.

Given the result of the interface research (Chapter 3) that highlights the continued importance of plans and that procedural modelling can be used to convert a plan into a 3D model, it was deemed a logical approach to use a form of procedural modelling to implement the 3D LIM. This decision should also be considered in light of the fact that landscape architects often create plan forms for their designs as a matter of course. Therefore, implementing a system that allows them to continue to draw a plan alongside which a 3D model is automatically constructed seems a sensible step.

There is a trade-off in procedural modelling between the speed of construction and the complexity of the resultant model. Therefore, to attempt to keep the user interface interactive, a basic form of procedural modelling was implemented. It employs the Hoinkes and Lange approach of parametric creation of landscape elements and is similar in design to the approach taken by SmartTerrain system [28]. It was also felt that the basic forms that the parametric approach was able to construct suited the outline design phase of a project when a designer is working with shape and form rather than finalised building materials.

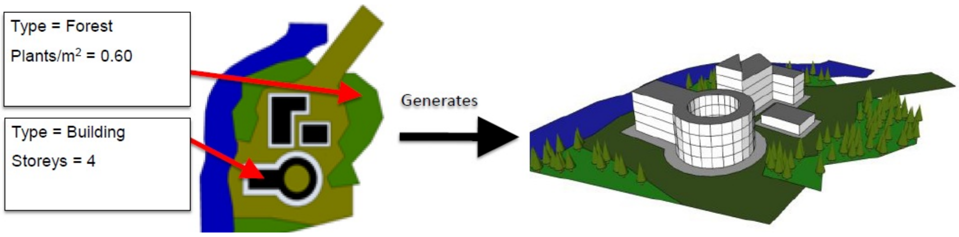

Figure 31 - Generative landscape modelling system

To form a 3D landscape model, a 2D plan of land usage regions (stored as linear polygons) at the surface is created. Each region is assigned to land usage type and can have internal holes. Each land usage type has a defined set of parameters associated with it. It is these parameters that are interpreted by the parametric system to construct the 3D model. A simple example of this is demonstrated in Figure 31. The system can also reference terrain data for the region and use this within the construction of the 3D model.

The parametric system is written in C++ and each land usage type is connected to a constructor object that holds the definition of the parameters for that land type and the algorithmic rules for constructing a 3D model. A constructor object is responsible for taking the input of each polygon region and relevant parameters and applying the construction rules to form a 3D geometric description of the resultant model, as shown in Figure 32. A constructor object may be responsible for one or more land usage types, especially ones that have similar 3D forms. For example, the built-form constructor is registered to handle both buildings and wall regions.

The 2D plan can be passed to a parametric controller object, which is responsible for passing the region to the relevant constructor class. Constructor objects are registered with the controller and this allows simple extension of the available land usage types. When constructing a 3D element, the constructor object also has access to terrain data, which it can use as a guide for construction of an object. For example, when creating a building, the built-form constructor will sample the height of the terrain around the polygon region and create the base of the building according to the lowest point. If a region is completely untagged it will be forwarded to the null constructor, which will not generate a 3D model.

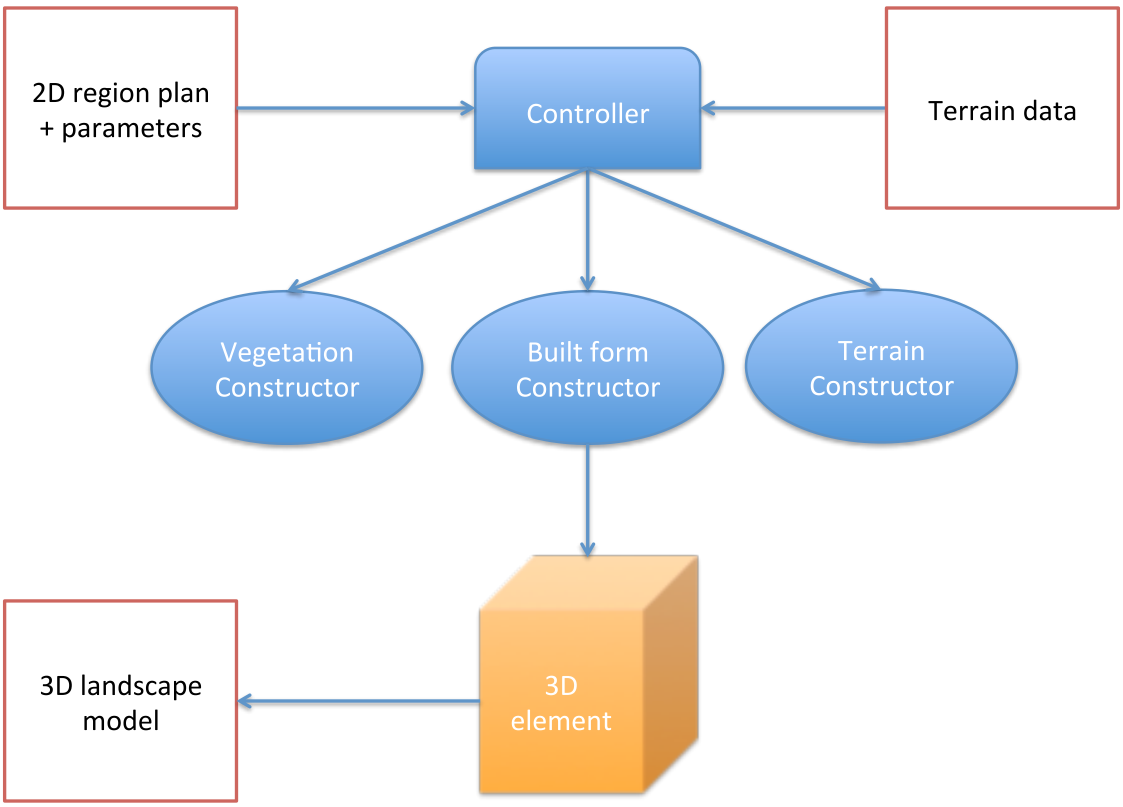

Figure 32 - Parametric construction system overview

A basic set of constructor objects has been created: terrain, built form and vegetation. The terrain constructor takes different categories of land usage and constructs a constrained Delaunay triangulation [82] based on interpolated point samples from the underlying terrain raster data. If there is no height data available to the system, then a simple tessellation of the area is performed. The built-form constructor creates simple extrusions of buildings and walls. The vegetation constructor is based on the terrain constructor, but has parameters that allow randomised placement of vegetation models to be automatically placed into that area of the landscape model.

Once the 3D surface has been constructed, a similar type of constructor is available for any available parameterised point data. For example, this is useful for placing known points of trees or lamp posts into the model. Currently, this constructor uses the parameters to specify one of a known set of existing 3D models and instances this in the correct position. The base height of the object is defined by the modelled landscape surface created by the region constructors.

The generation system produces geometric 3D models, but it is not connected directly to any form of 3D rendering. Therefore, it has been integrated into two existing software packages to allow a user to view the constructed objects. Initially, it was integrated into Sketchup, and it operated successfully for simple 2D plans. Sketchup was chosen for the following reasons: that it has an open API that allowed the parametric system to be integrated; it has a comprehensive set of editing tools that would allow alteration of the polygonal map; and Sketchup allows quick movement between the 2D plan and 3D views, and NPR visualisations.

An additional interface was created that allowed the editing of parameters for a region when it was selected in the Sketchup editing window. The parametric interface and resulting 3D landscape model are displayed in Figure 33.

When considering site design, the first major issue with construction of a 3D landscape model is the need to create a model of what is currently “on site”. Some local authorities possess 3D models, but these are not necessarily in a format that is easily editable and it is often hard to get access to these. However, in the UK, it is possible to get polygon data for a site from Ordnance Survey Mastermap[19]. This data is provided in various formats, but the most useful in this instance are polygons and linked attributes stored in GML format, which identify the type of region. Therefore, an importer for Mastermap data was created that took a GML file for an area and converted it into valid regions and parameters that the construction system could understand. To automate the creation of building heights, the importer also needed access to a raster layer of data derived from surface LIDAR and a processed bare earth version of the LIDAR, which when differenced in GIS provided a reference source for building heights. For each building, several random point samples taken across the building region were used to give an average building height, which was then converted into storeys via an average setting for storey height of 4m. Thus, given an area of Mastermap GML, the corresponding terrain data and height differential data, the system could provide a base model of the site to be constructed by simply specifying the location of three files.

[19] https://www.ordnancesurvey.co.uk/oswebsite/products/os-mastermap/index.html

A second importer was also implemented to allow transfer of GIS point data into the 3D model. This was used to import the surveyed position of trees from ESRI Shapefiles that covered the area of interest, as this information was not present in the GML data. A lot of information appropriate to 3D landscape models is held in GIS and to prove it was possible to rapidly import this type of information was of worth.

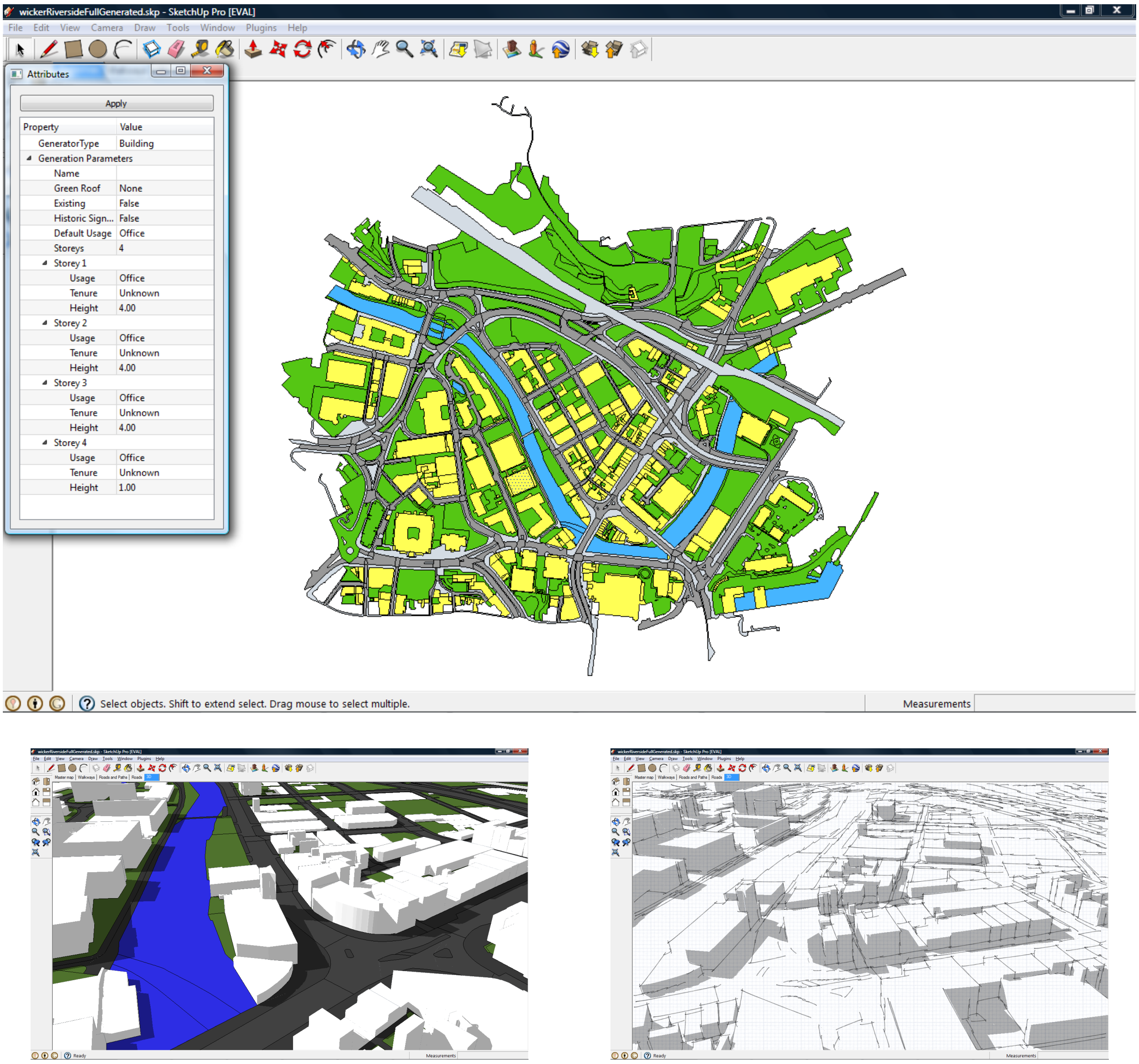

Figure 33 - Screenshots of the Mastermap plan, generated 3D model and NPR render of 3D model

The map import into Sketchup via the plugin is not an interactive process, but once imported, it was possible to interactively edit the 2D plan and update the 3D model accordingly. If polygon regions, including any surrounding regions, were altered or any parameters changed, the system would remove the existing model elements and replace them with regenerated ones that incorporate the user defined alterations.

However, with the Sketchup integration the user had to toggle between the 2D plan and the 3D model, which broke the requirement for seeing the 3D alongside the 2D plan.

5.2 PROVISION OF AN INTERACTIVE 3D WALK-THROUGH VISUALISATION

Consequently, although the integration to Sketchup was successful it did not have good support for an easy to use, interactive eye level walk-through visualisation. Therefore, the generator plugin was integrated into another existing landscape modelling software package, Simmetry 3d. The Simmetry 3d plugin API allows for a higher level of customisable actions than the Sketchup Ruby API and it contains features to maintain real-time performance whilst showing models containing large vegetated areas. As Simmetry 3d is based on computer game technology, it allows an instant transition from an interactive 3D CAD style design mode to eye level "walk-throughs" of proposals (Figure 34) controlled by a video game console controller.

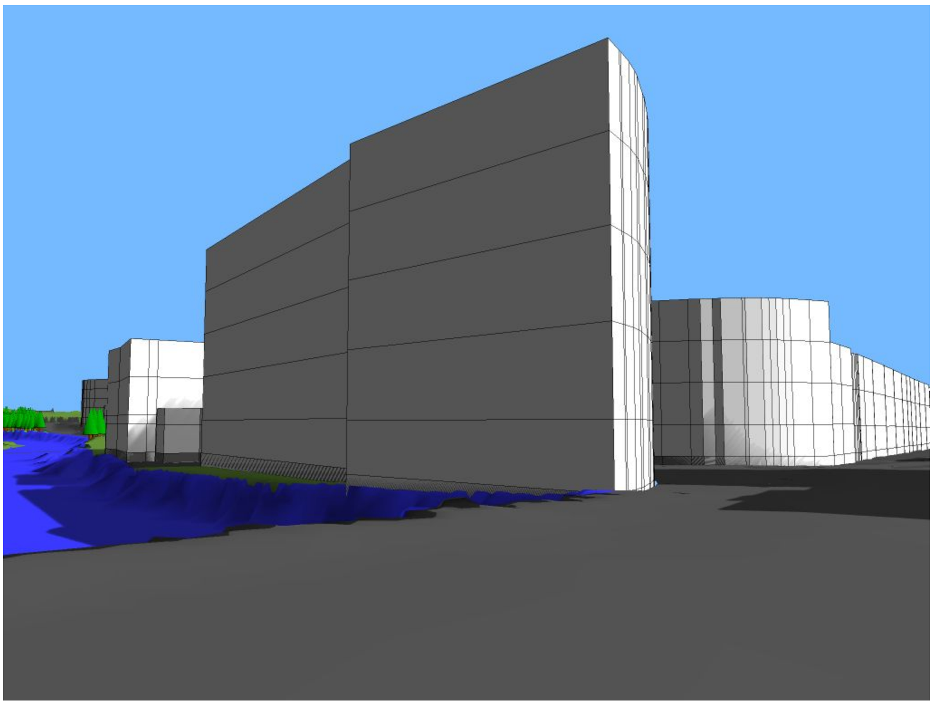

Figure 34: A generated 3D model displayed inside Simmetry 3d computer eye level walk-through

The inclusion of the generator as a plugin into two independent 3D modelling packages led to an interesting side effect. The 2D plan, attributes and terrain data were now able to fully represent the landscape model as a file interchange format between the two software packages rather than having to export and import 3D geometric data. This could lead to a reduction in the amount of stored data depending on the complexity of the generated models, although the disadvantage is there is computation needed to display the model once it is imported. However, again the issue remained that the user would need to toggle between the 2D plan and the 3D visualisation rather than having them available at the same time.

5.3 DEVOLVED INTERFACE

To overcome the problem of the user being forced to view only the 2D plan or the 3D model, a slightly different approach was taken. Simmetry 3d was able to display the 3D model in walk-through and in 3D CAD view more efficiently than Sketchup. Sketchup provided easy to use tools that supported region based editing, which was a feature lacking in Simmetry 3d. Hence, the ideal scenario was to use a combination of both software packages, i.e. display a 3D model in Simmetry 3d and edit the related 2D plan and parameters in Sketchup. Therefore, the plugin inside of Simmetry 3d was extended to add a TCP/IP server that would allow one or more clients to connect and download the current 2D plan and attributes. The Sketchup plugin was changed so that it would act as a client. Google protocol buffers[20] were used to create a custom protocol for sending and receiving polygons and attributes. This architecture is displayed in Figure 35 where the orange colouring represents the developed plugin. Each client is able to send out changes to polygon and attributes back to the server, which will broadcast these to all other connected clients and update the 3D model using the parametric generator system.

[20] https://developers.google.com/protocol-buffers/

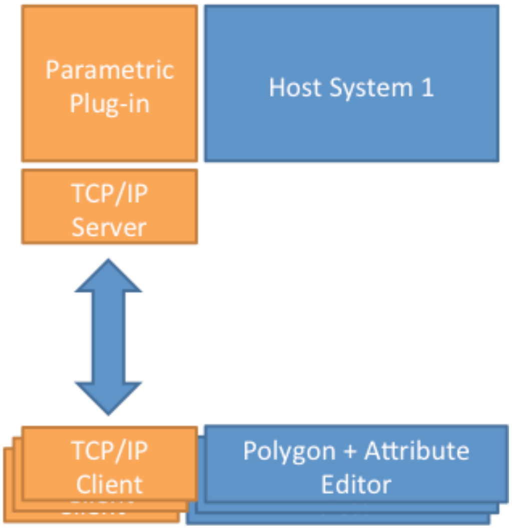

Figure 35 - Devolved editing architecture

All this had the effect of devolving the task of editing the 2D plan and parameters to the client and away from the 3D model. In the course of this research, consumer level tablet devices that provided high resolution touch screens and wireless networking became available. A client was implemented on an iPad to handle connection to the server. Although full editing functionality was not implementing in this client due to time constraints, it was proven capable of connecting to the 3D model server to download the current plan and attributes. Parameters could be altered using this client allowing a user to select a region and edit attributes or region type.

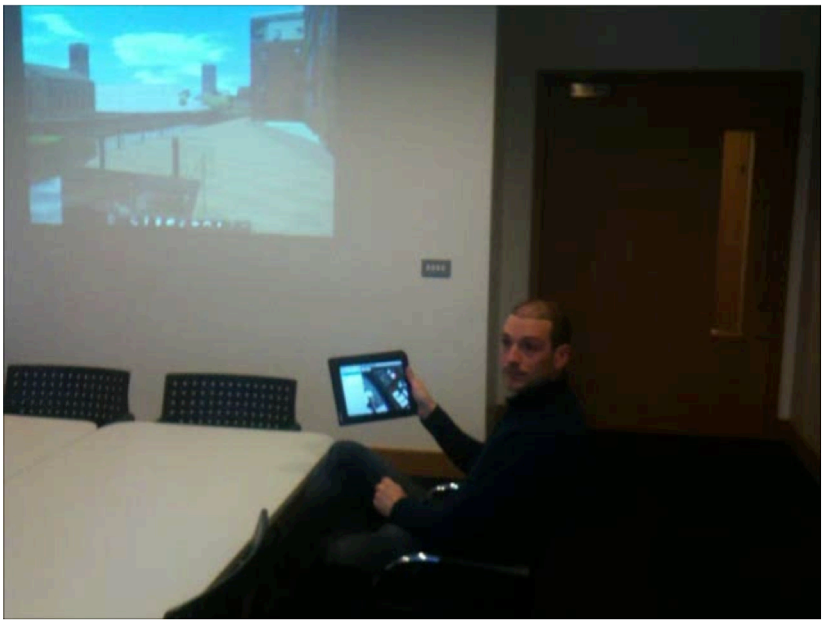

Figure 36 – 3D model interaction devolved to a tablet device

The movement of the camera in a Simmetry 3d walk-through is controlled by either the keyboard or a game controller, but the tablet can offer a different form of control interface. The client/server protocol was also extended to allow control of the position of the viewer within the Simmetry 3d walk-through mode. The server would render a top-down image of the landscape model, which was sent to the tablet and overlaid on to existing satellite imagery. This movement control interface works with any model loaded into Simmetry 3d, whether procedurally generated or manually created. The current position of the camera in the walk-through visualisation would then be highlighted in the tablet view via a red circle with a line denoting direction as shown in Figure 37. This is similar to the more tangible “lightwheel” interface approach of Werner et al [63].

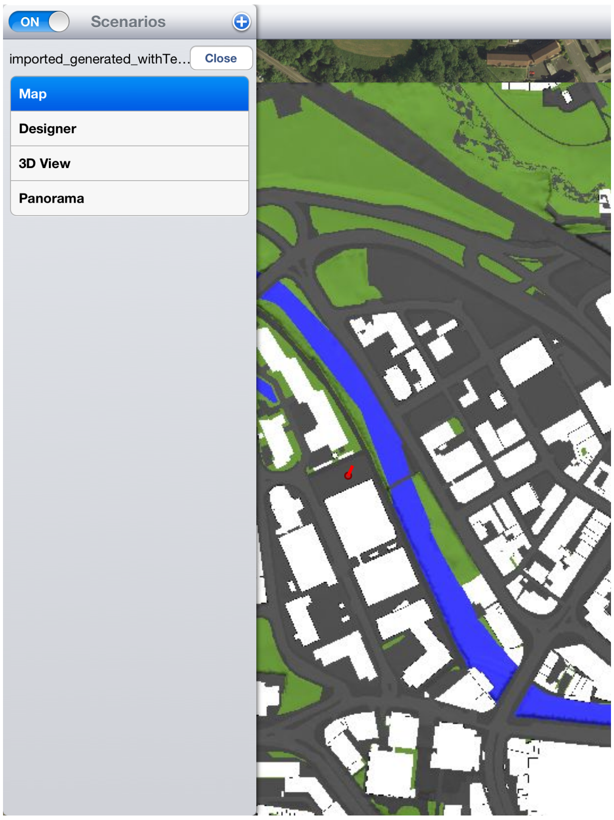

Figure 37 – Tablet interface for controlling the position in a Simmetry 3d walk-through

The user was able to press on the map to select a new position with a swipe to define the direction of view. The view would be set to the maximum height in the model at that position. For example, if the user selected a position over a building the view would be set to the top of that building. It was also possible to provide movement buttons to allow movement of the view laterally and vertically.

The tablet application was also written to enable connection to multiple servers, which can be seen in the left hand panel of Figure 37, where it is connected to two different proposals for the same piece of land. When connected to a procedural model it would be possible to edit the parameters for a region and see the change within the walk-through visualisation.

The tablet control interface (as a movement controller only) and a video game controller, which were connected to a Simmetry 3d walkthrough visualisation, were demonstrated to 16 people in small groups. Some of the participants tried using the interface devices, whilst others did not. After the groups had at least 10 minutes exposure to both devices, these participants were asked the following question: "Which interactive 3D model control method did you prefer?" The results of these very basic trials are shown in Figure 38 with the video game controller being most preferred and the tablet interface close behind (see Appendix C for questionnaire layout).

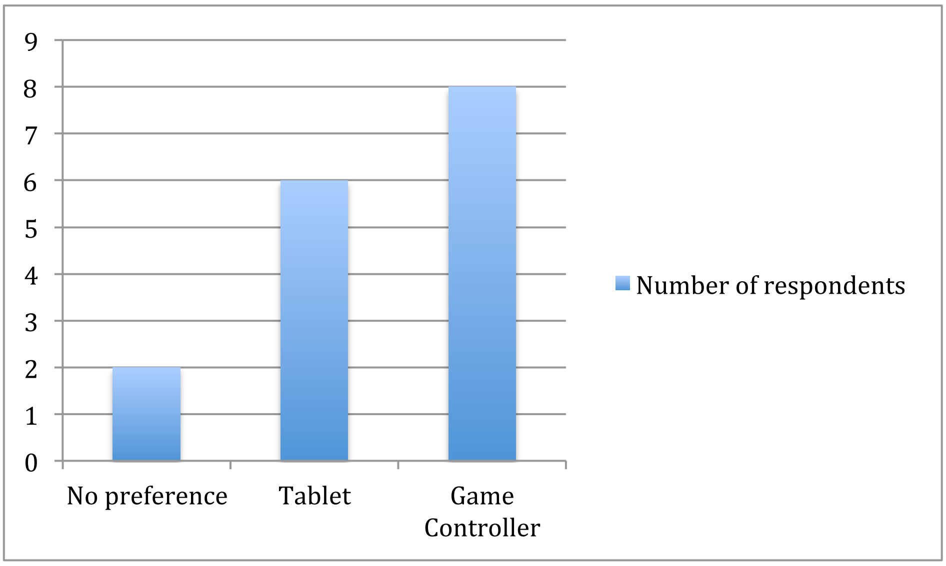

Figure 38 – Preference for controller type

However, the sample size is small and the fact that some participants tried the interfaces while others just observed means that it is hard to draw too many conclusions from this data. The tablet interface certainly allows instantaneous movement from one position to another within the model, whereas the video game controller would require the user to journey across the landscape. Nevertheless, it is possible that users may also want this "journey" experience to better understand the design. These preliminary findings should give pause for thought about the best form of interface to interactive 3D landscape visualisations and this is probably an area that should be further researched. Perhaps an interesting option would be to combine the tablet and video game controller interfaces to offer both to the user.

5.4 ANALYSES INTEGRATED WITH THE LANDSCAPE DESIGN

It was hypothesised that the parametric generation system would be a method of integrating linked assessments to the design held in the 2D plan and 3D model by providing the modelled 3D elements with non-geometric information about that element.

To prove that this was indeed the case, a generated 3D Sketchup model was connected to a financial physical model, based in Microsoft Excel[21], that predicted financial viability for new buildings.

In previous work Henneberry et al [83] proved that manually drawn Sketchup models could be linked to a financial model. One of the main inputs to the financial model was the type (industrial, residential, or commercial) and the area of floor space available in new buildings. To calculate the area of floor space per building, each floor of a building would be drawn as a rectangle in Sketchup at the correct storey height and a pre-defined Sketchup layer style (representing the allocated floor usage) was then assigned manually to each rectangle. Once the design was completed, a Sketchup plugin script could then iterate the areas per style and calculate the total area per floor usage. This method worked, but it proved time consuming having to draw each floor of a building by hand and could be error prone due to wrong assignments of floor areas.

Parameters added to the built form constructor for buildings were: a building identifier, the number of storeys, a default floor usage for that building and the proposed usage per floor. This allowed the user to draw an outline for a building and assign the floor usage. The procedural generation of that building would then create a 3D building model including internal floors. Each floor was automatically tagged with key-value attributes, specifying the proposed usage of that floor. It was then possible to iterate through the structure of the 3D model (in a Sketchup plugin that allowed the calculation of the area of each floor per usage type per building) to create the values that were then placed into the financial model in Excel. The results of this query of the 3D landscape model were then displayed to the user in the form of Excel charts. The calculations in Excel took longer than a second, so this model integration cannot be called real-time. Nevertheless, it is likely that

[21] http://office.microsoft.com/en-gb/excel/

converting the logic from the Excel sheet to native code could provide real-time performance, in which case it would be possible to run this style of integrated model interactivity.

The tagging scheme used by the constructor objects is key to the creation of a semantic 3D landscape model with separate values per landscape region. It is these tags that allow subsequent integration of the generated 3D model after its construction.

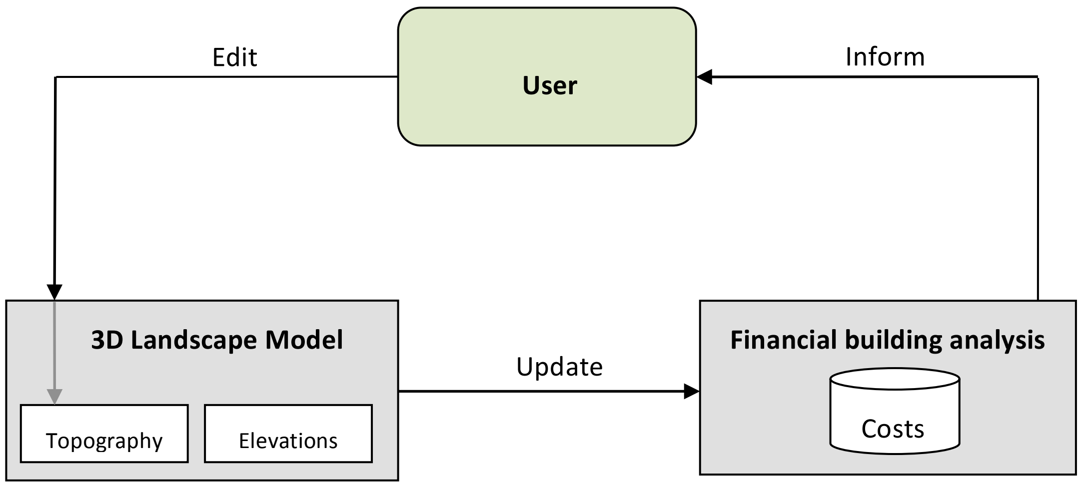

Figure 39 – Integration of the financial building analysis with parametric 3D model

At this point, the system had all the desired functionality of the Edit-Query-Inform cycle of the 3D LIM. As demonstrated in Figure 39, the 3D landscape model, built on terrain and polygonal topography was now integrated with the cost database of the financial building analysis, which would update in response to the user editing the landscape model through the 2D plan.

Given the need to calculate areas of land usage for the linked financial model to allow real-time feedback, a different approach was taken to this problem. By utilizing the speed of the GPU, it would be possible to calculate the amount of land usage, but it would also be possible to highlight specifically tagged areas in the model at the same time.

After discussions between the author and a developer of Simmetry 3d, the Simmetry 3d API was extended. A rendering function was added to the API to allow the 3D model to be falsely coloured based on an element tag and the possible values in that tag. This rendering function takes a mapping of tag values to colours. Using this mapping, the false colour render pass reduces the 3D model into a resultant coloured grid, which can be interrogated using the reverse colour to value mapping. The renderer function is flexible and can produce any resolution of grid required for the entire modelled area, or a subset of this area depending on the user requirements.

By rendering based on land usage, it is possible to create an in memory raster grid of the land usage of that model. This can be used in two ways. Firstly, with the pixel scale known, the pixels can be processed to give an approximation of the total land usage per tagged type. The higher the resolution of the rendered grid, the lower the overall error will be from rasterising a vector plan. However, there is a trade-off in that the higher the resolution, the more time will be required to generate the grid. Secondly, the land usage grid can be used as an input to a OpenGL graphics shader[22] program that allows the underlying 3D model it is based on to be coloured by land type. An example of this can be seen in Figure 40, which shows in green open space that is tagged as publicly accessible and private space, shown in red.

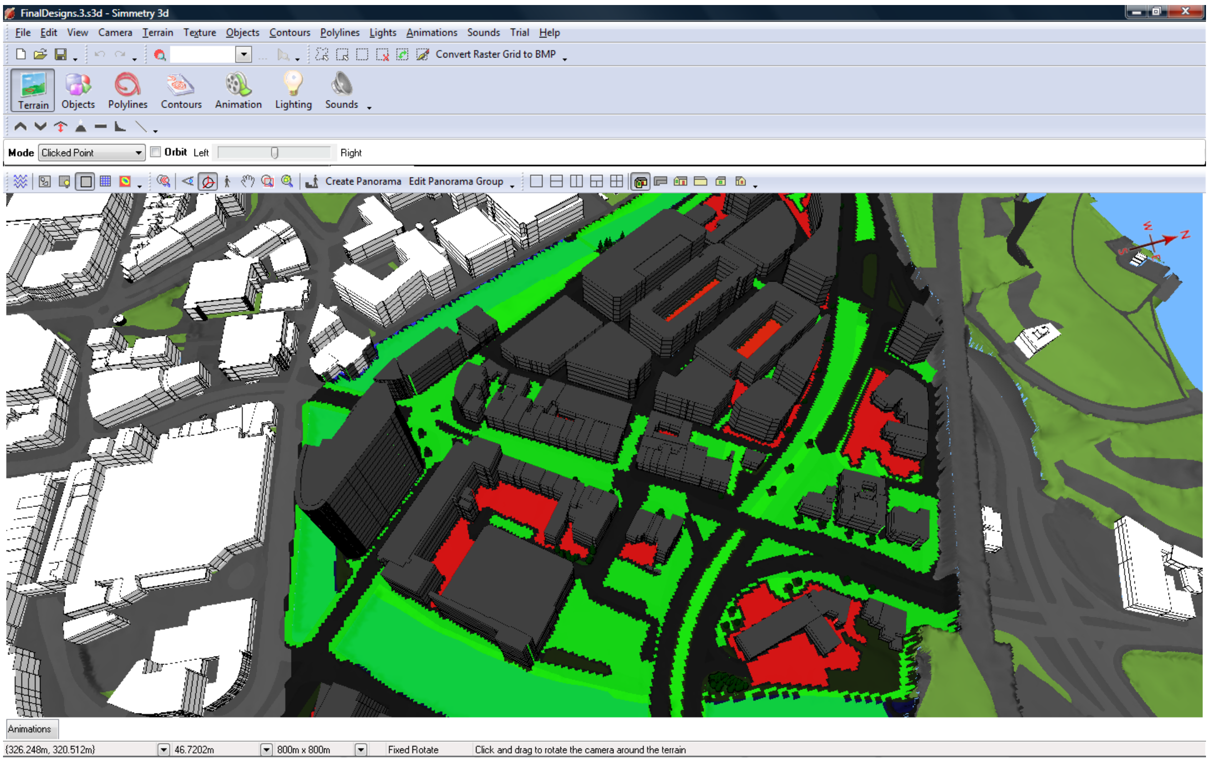

Figure 40 – Highlighting of public (green) and private (red) space in a design

[22] A graphics shader allows programmatical control of the GPU hardware

A set of different geo-spatial assessments was added to the system based on this tag to raster scheme and these could be interactively toggled between. A user interface was constructed to allow the user to switch between these assessments, as shown in Figure 41. When selected, each assessment was also able to construct an HTML output that was then displayed in the lower panel of the assessment user interface. The example shows the percentage cover of each type of open space and calculated area. The user was able to manipulate the blend of the highlighted assessment to the colour of the underlying model interactively using a slider control. This would allow the user to switch back to the original model or mix in the geo-spatial assessment at the blended level required.

Although these assessments are not as accurate as the polygonal area calculations used in the financial model linkage, they can be calculated interactively when a design is edited and can highlight the design elements spatially.

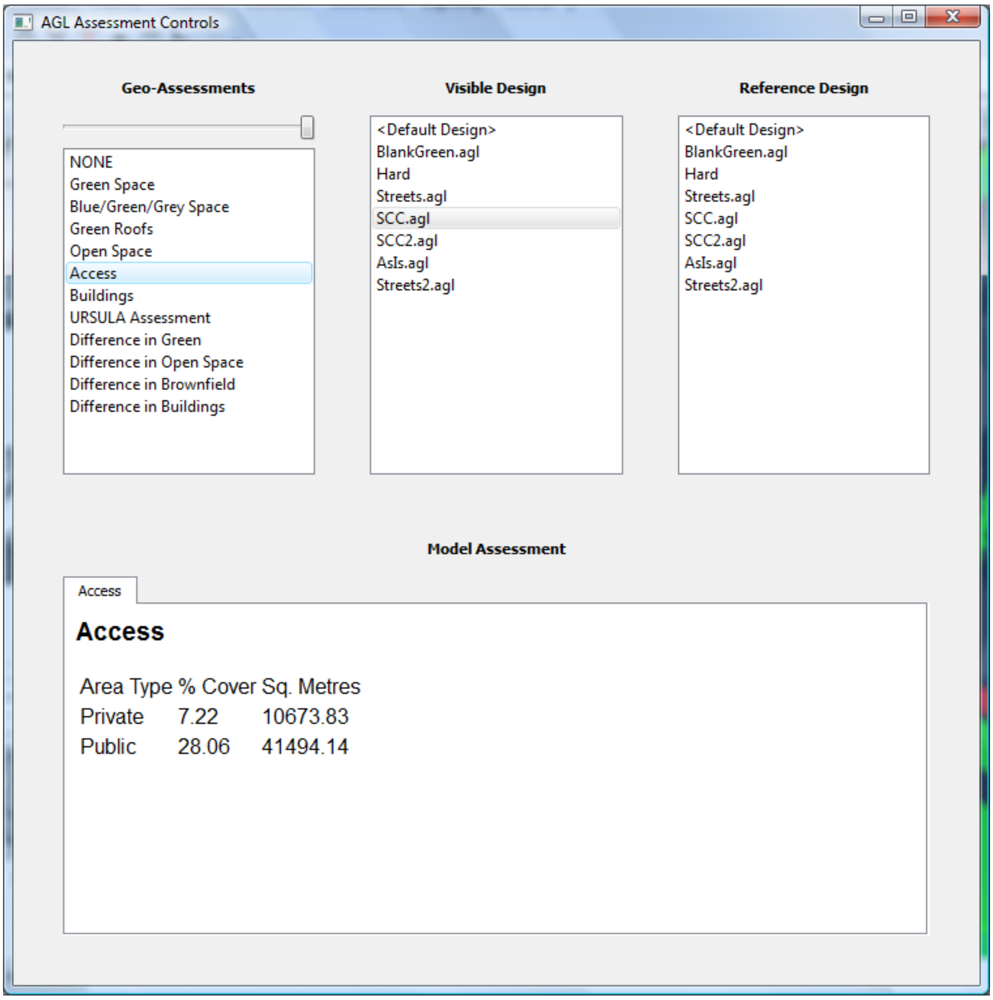

Figure 41 – User interface to switch between geo-spatial assessments

5.5 STORAGE AND COMPARISON OF MULTIPLE DESIGNS

Once the system could generate and analyse one design successfully, it was extended so that a user could easily make a copy of the 2D plan and attributes currently being edited. This would create a new *version* of that design. The 3D model of this new version would then be generated and stored automatically. An interface to these versions was created so that the user could quickly move between different versions of designs. A list of versions can be seen in the top central column of Figure 41.

The introduction of versions allowed the geo-spatial assessments to be extended to calculate and spatially highlight areas of difference between two versions. This was achieved by rendering the relevant tagged objects in the reference model (selected in the top right column in Figure 41) and then again with the currently visible version. The variance between the designs can then be calculated by differencing these two raster grids.

The author believes highlighting the differential between designs could be a key feature for a 3D LIM. The user interface not only produces a report of the differences in area of a particular land usage, but it can also show spatially the differences between the designs. Figure 42 shows there is a 1.14% overall gain in green space over the "status quo", but the proposed space is distributed rather linearly through the design and existing blocks of green space are lost.

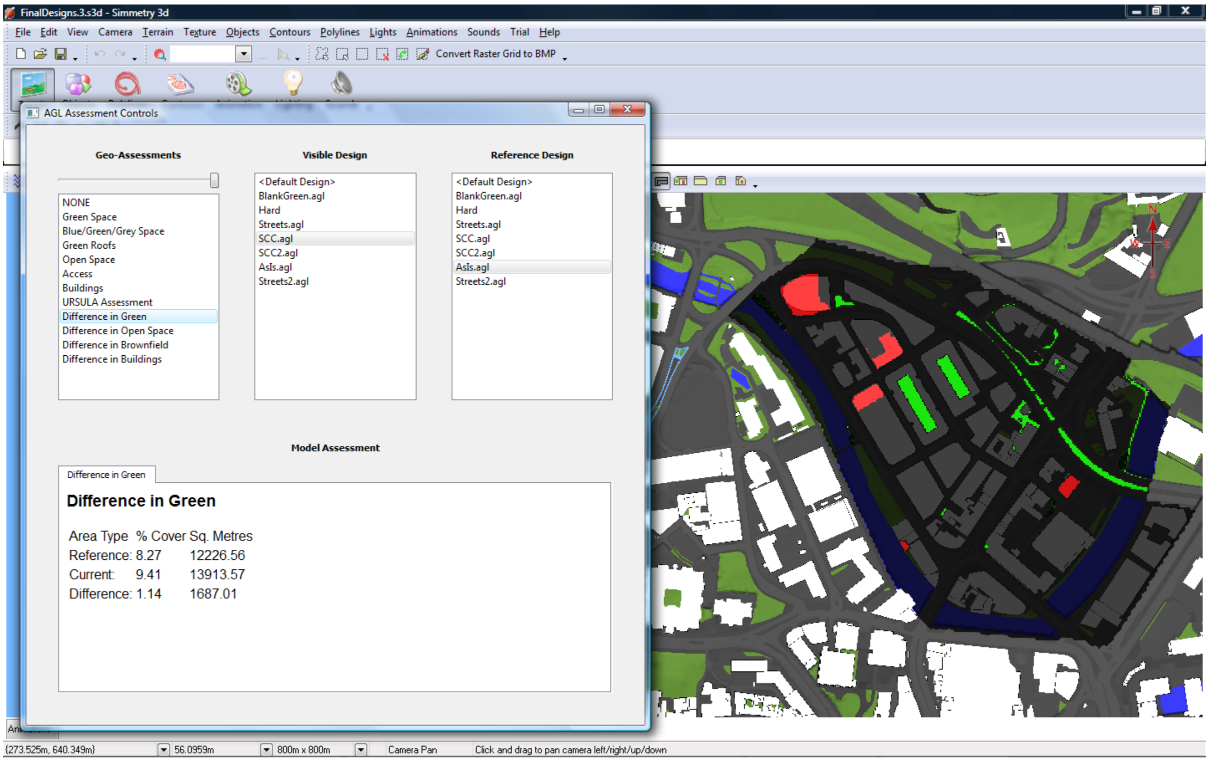

Figure 42 – Difference in green space (red shows loss, green shows addition) between two designs.

5.6 DISSEMINATION OF THE DESIGN

The final role a 3D LIM must perform is to be able to output intrinsic data in as many ways as possible that support the user. Using the prototype 3D LIM, it was simple to produce interactive 3D visualisations and static 3D imagery using an existing function in Simmetry 3d to save an image. As has been mentioned previously, plans remain highly rated in usefulness for understanding a design. Therefore, an exporter was created in a Sketchup plugin that allowed the 2D plan and attributes to be saved in a common GIS format. This allowed additional GIS visualisation and spatial analysis to be performed on a design.

The initial reason this export functionality was developed was to allow 2D plans to be converted to coloured maps based on the parameters. Eventually this functionality was integrated into the Sketchup plugin. The embedded plan colouring feature meant a user could interactively alter the 2D plan to represent various different shading patterns based on the parameters of the regions. Several examples of these are shown in Figure 43, which shows the editable 2D plan coloured by the default land usage style, by ecological usage, by building usage and by building height. This visualisation of the modelled parameters could help the user to quickly confirm correct assignment of parameters to the model.

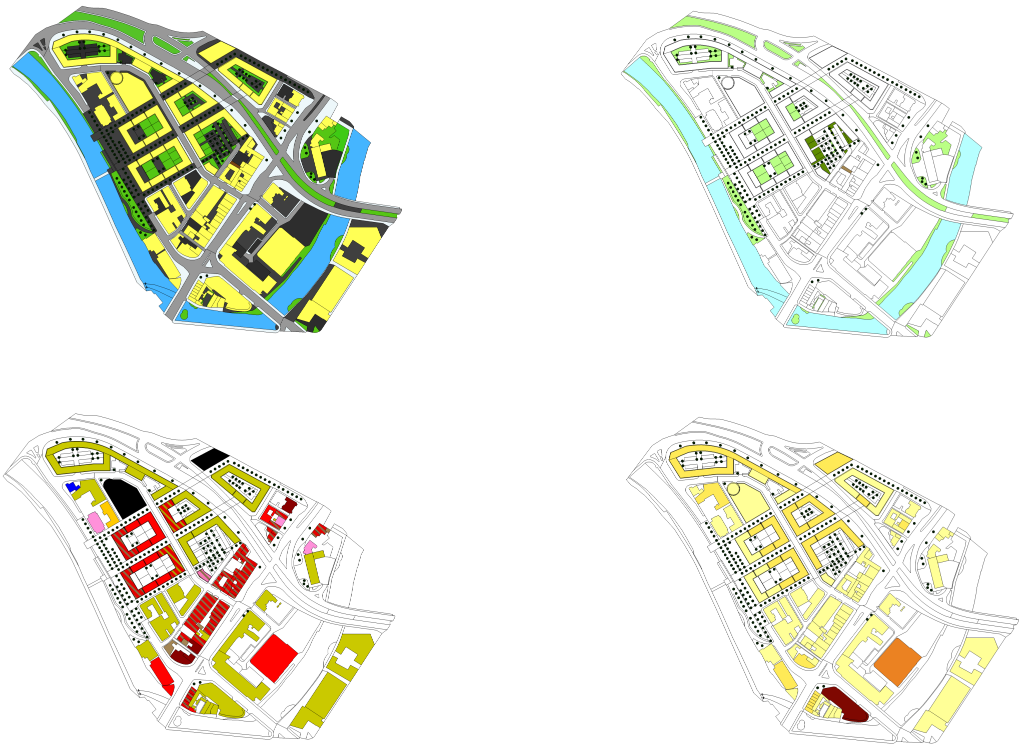

Figure 43 – 2D plan colouring styles in Sketchup, (clockwise from top left) land usage, ecology, building heights and building use

The system was installed on a laptop with a Core 2 Duo 2.2Ghz processor, 4GB of RAM and an ATI Radeon HD 3400 graphics card. This meant it was portable and possible to use in a remote setting, such as a charrette or a public consultation meeting. It could be operated with one screen, although it would be beneficial to have two screens or projectors (one for the 2D plan and one for the 3D visualisation). The system was also able to run in a Virtual Reality studio with stereo glasses support through the features in the Simmetry 3d software.

5.7 Results

To test the system, a site (800m x 800m) of urban riverside in the UK was selected. The LIDAR data and Mastermap GML data had to be obtained from the Environment Agency and the academic Edina

Digimap[23] service respectively. These were then imported into a Simmetry 3d project, which was then geo-referenced to the Ordnance Survey Great Britain 36 projection. The LIDAR data was imported into the Simmetry 3d project at 0.5m x 0.5m resolution. The surface LIDAR and the raw LIDAR trace were then processed in Arcmap to create the height difference data for the buildings. The categorised vector plan for the site was imported from GML importation. This took 12.9 seconds and resulted in a 2D plan containing 2125 categorised regions. The automatic generation of the 3D model then needed just under 16 minutes to complete. Currently, all buildings are generated as massing models with flat roofs. A further development for the importer and building generation object could be to improve the detection and generation of the building roof from the LIDAR data, using techniques similar to Laycock and Day [84]. Furthermore, it is worth considering procedurally mapping textures to the buildings in an texture memory efficient manner similar to Laycock et al [85], ESRI CityEngine, or using socio-economic data to inform texture choice [86]. These techniques rely on the self-similarity of objects within the urban environment, but for a landscape model to perform as a design tool the textures may need to represent actual on-site detail, which might involve some form of process to automate texture mapping from street level imagery databases, such as Google StreetView[24] . In addition to this, it would be interesting to understand how more complex procedural modelling would support the landscape design process as it moves from outline design to more detailed design stages.

The collection of data and conversion for the site were the most time consuming steps in this process. Firstly, it was difficult to obtain accurate terrain data for the site and the data preparation stage relied heavily on expert knowledge to prepare the various datasets in the correct format for use with the system. Back in 1999, Danahy pointed out that software and hardware were no longer the constraining factor for the construction of 3D landscape visualisation, but instead it is the collection of data to inform the model construction, either manual or procedural [87]. It seems that this problem still exists today and availability of data and that data being in the correct format for sites remain issues for any implementation of a 3D LIM.

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[23] http://digimap.edina.ac.uk/digimap/home

[24] http://maps.google.co.uk/intl/en/help/maps/streetview/

Connecting Sketchup to the 2D plan server takes 9 minutes to complete, due to what appears to be an $O(n^2)$ slowdown on inserting of new regions into the 2D plan held in Sketchup. The tablet interface does not have this issue, and the 2D plan is available over a wireless LAN within 3 seconds. To overcome this slowdown whilst the prototype was being developed a reduced area of the plan was used, which imported in a significantly reduced time. Once the plan is active in Sketchup, it is possible to interactively edit the model using the in-built drawing tools and the parameters GUI, even with a geo-spatial assessment running. However, the response time of the system can be adversely affected when edits occur that affect a large number of regions. This may have an unfavourable effect on the user, but a multi-threaded approach may be one way to alleviate this.

The prototype demonstrates that the addition of a set of key value pairs to each element that builds up the 3D model is one method for linking to spatial analysis of a design. The tagging system represents a generic method for the procedural generation to calculate additional information based on the input parameters and the generated model. Combining these tags with a GPU render pass offers a rapid technique for analysing a landscape design, showing the results within the context on the 3D model, and producing more standard figures and graphs. Chapter 6, Chapter 7 and Chapter 8 will continue to expand on how this approach has been used to link the 3D LIM to different styles of analytical models.

While the prototype is successful in proving the feasibility of key features of a 3D LIM, it also suffers from a series of limitations. One limitation in the prototype is that if the user wishes to alter the terrain on a site, a manual method is required. Terrain modifications are achieved by the user employing the terrain sculpting tools on the LIDAR data loaded into Simmetry 3d and then regenerating the regions around that area. It may be worth investigating if it is possible for a designer to control terrain modification through a set of parameters and the procedural generation system. Another problem is that the regions are constructed in isolation and this can cause small gaps to appear in the surface of the model, when the sampling of the region boundary occurs at a different spacing on both sides. It would be better if a region could reference its neighbouring regions in order to marry the vertices of adjoining generated meshes. With the current prototype if a region does not exist in the model then no corresponding 3D element will be created, leading to holes appearing in the 3D landscape model. It may be better therefore to consider a whole site as having one overall "master" region that would, by default, generate terrain to avoid these holes.

Utilising the multi-processor architecture of the GPU through graphic shaders proved it was possible to display spatial results of linked assessments interactively. The system could calculate and respond within the allotted time period, whether the user was viewing or editing. However, the blending of the coloured geo-spatial assessment results with the underlying 3D model colour might cause misinterpretation of the data if strongly coloured regions are overlaid. Therefore, a better approach may be to toggle a grey scale colouring scheme for the 3D model that can be blended directly with the coloured assessment data.

A design in the prototype was also combined with a manually modelled and textured 3D landscape model. As the existing hand created model was constructed from the same map data source as the 2D plans imported into the prototype, holes could be cut at known region boundaries in the manual model. This allowed the exact positioning of the imported regions within the higher fidelity model. This approach may prove useful if existing models could be re-used to provide visual context to the procedurally generated models. Lynch states that people form their understanding of an area via several types of urban formation: paths; edges; districts; nodes; and landmarks [88]. This will probably be similar for users of interactive 3D visualisations, so providing recognisable areas and landmarks that are fixed elements in a design alongside the procedurally generated 3D elements may improve cognition of designs. Figure 44 shows an example of this with the river forming an edge and the historic mill buildings on the left hand side of the screenshot acting as a landmark.

Figure 44 - Editable procedural models inside a manually constructed model

Chapter 6

BAYESIAN NETWORK INTEGRATION

There exists a large body of knowledge, especially domain specific knowledge, in the minds of experts. Consequently, modelling techniques are being developed that attempt to take account of this rich reserve. One such method for knowledge capture is to construct Bayesian Networks (BN). BNs allow for causal relationships (probabilities) to be specified based on subjective assessments (“expert opinion”), empirical evidence, data derived from existing models, or a combination of all three, making them particularly suitable for integrating predictive information from multiple disciplines [89]. As a black box model to a 3D LIM, they present a set of outputs, which are dependent on a set of inputs and internally define the probabilistic linkages between the inputs and outputs. Duespohl et al [90] reviewed the use of 30 BNs created for participatory sustainable environmental modelling and management and concluded that BNs can be used successfully, although they recommend that BNs be connected to GIS. Two domains where BN have been employed include integrated catchment management [91] and urban river corridor redevelopments [68]. Sustainable management of the areas surrounding an urban river is a complex task that, increasingly, involves finding a compromise between the views of multiple stakeholders that may not easily be brought to consensus. Since some outcomes of management interventions are more abstract or intricate in nature, proving harder to capture than simple data driven models, new predictive BN models are now being developed to help address these challenges. Incorporating expert opinion is important because, as is often the case in integrated catchment management, domain expert opinion can be used to create BNs when there is a paucity of data. However, while increasingly sophisticated modelling techniques are being developed, a barrier to their uptake by water managers is their complexity, and lack of a user friendly interface [92]. So, whilst BN are generally computationally cheap and, as such, provide an interactive method for exploring design options, they often do not present a user friendly interface for non-expert users. An example of a small BN user interface is shown in Figure 45.

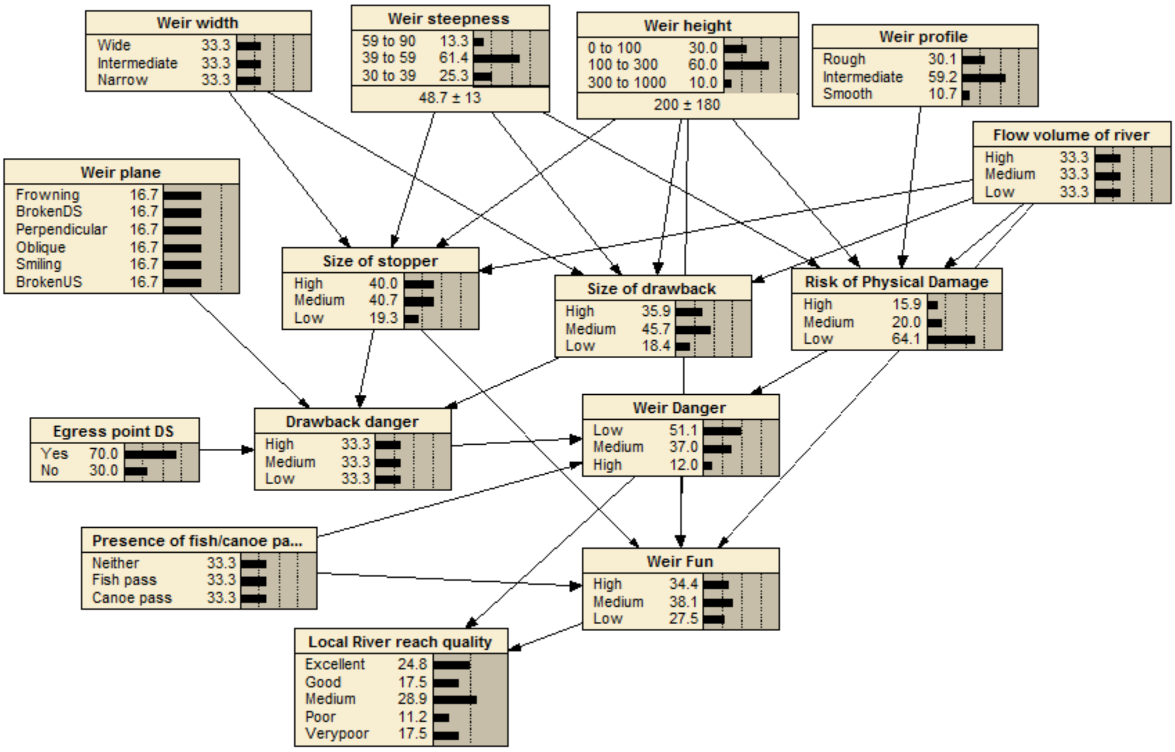


Figure 45 – User interface showing a BN to predict weir danger and fun for canoeists [93]

Thus, a 3D LIM with the complementary strengths of both techniques (aiding the understanding of the visual nature of proposed interventions and making it possible to assess their impact on abstract non-visual criteria) might be expected to become a useful decision making tool. Proposals for changes to river corridors could be fed into the system via user alterations to a 2D plan and these alterations could be assessed utilising the knowledge of experts captured in the BN. It could be anticipated that the overall effect would be that the users of such a system will have an accessible method for increasing their understanding of the consequences of a design decision without the need for extensive training. In essence, there will be a transfer of knowledge from expert to user via the BN that will strengthen the process of decision making, as shown in Figure 46.

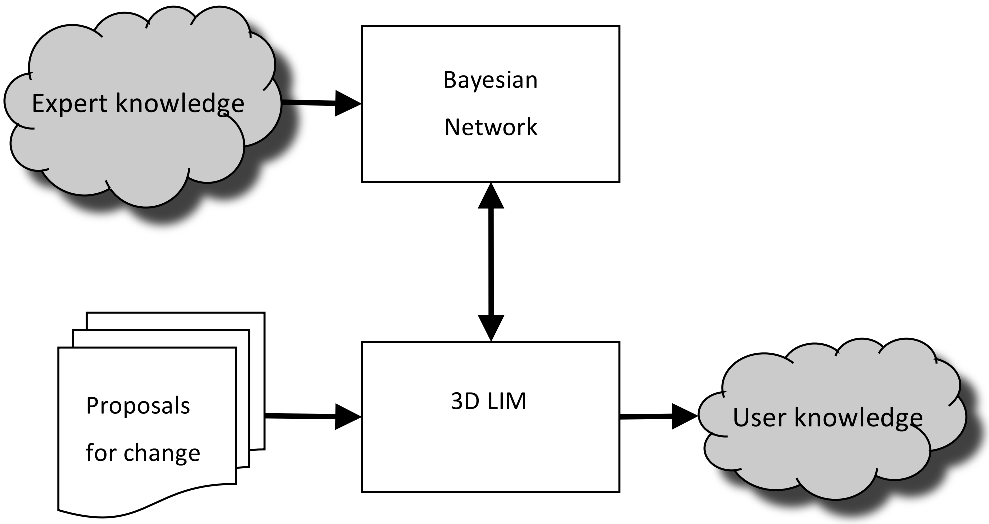


Figure 46: Conceptual model of linking BN to a 3D LIM

To explore coupling a BN with a 3D LIM, it was decided to integrate a small BN that captured canoeist knowledge of weir quality. Then, if that linkage could be established, a more extensive BN that attempted to consider sustainable design of urban river areas would be integrated into the 3D LIM. Section 6.1 details the weir quality BN integration and then Section 6.2 explores the integration of the more extensive BN.

6.1 CANOEIST WEIR BAYESIAN NETWORK

Weirs on rivers are typically seen as obsolete industrial infrastructure for providing water flow to waterwheels. However, there is much interest from numerous stakeholder groups in modifying these weirs: some anglers would like to install fish passes; potential victims of flooding are interested in removing weirs; proponents of hydro-electricity want to install micro-hydro schemes; enthusiasts of natural history aspire to restore the river to a more natural state while enthusiasts of the river's heritage want to conserve weirs for their historic value. These modifications also determine the recreational quality of the river for canoeing, a major leisure activity on many British rivers. Weir height, steepness, roughness, plane (orientation relative to the river bank), and presence/absence of attached modifications all determine how canoeists perceive the fun and danger of the weirs [93]. Consequently, decisions on modifying the weirs must account for this abstract impact on the recreational quality of the river for canoeists. Shaw [93] constructed a BN that can predict the influence of weir modification on the quality of the river for canoeing, which was the initial BN chosen to integrate into the 3D LIM. This can be seen in Figure 45.

The 3D LIM procedural generation system was extended to contain a constructor object that had two distinct components: a 3D weir model generator and a weir assessment system.

The role of the 3D weir model generator is to procedurally construct 3D models of weirs, which increases the speed of generating models of the weirs and removes the need to manually construct models. The generator needs several inputs: a 2D polygon region that defines the extent of the weir, two independent edges along the polygon that define the upstream and downstream boundaries, and a distinct set of parameters that allow the user to implement various weir management options. The polygon area of the weir can often be derived from geographic map data, such as the Ordnance Survey Mastermap data. The parameters for the constructor are simple name/value pairs, such as weir ‘Height’, ‘Bumpiness’, ‘Number of Steps’ in the weir. As previously described, given these inputs the weir constructor object generates a 3D representation of the weir using the base polygon and parameters to inform the shape of the resultant model.

The canoeist BN has been developed using the Netica[25] software package that allows a BN to be defined using a standard graphical user interface. Each variable (node) in the Netica model has a series of discrete states, e.g. weir height is categorised as ‘High’ (>3m), ‘Medium’ (1-3m) and ‘Low’ (<1m). The nodes are linked in a cause-effect network and the relationships between them are described probabilistically. At the end of the network are indicator nodes: danger and fun of a weir from the viewpoint of canoeists and river quality, a combined function of the danger and fun. When the state of an input parameter is set, probabilities will propagate through the BN changing the states of the indicator variables. The compiled Netica model is then linked to the 3D weir model generator through the use of the Netica Application Programming Interface (API). An advantage of using this API is that the system maintains a separation of the BN from the visualisation system and 3D model generator, which allows refinements to be made to the BN outside the visualisation host program that feed directly into the model assessments.

[25] http://www.norsys.com/netica.html

As a weir model is generated, the various key/value parameters are fed into a weir assessment module in the form of input variables. Additionally, the geometry of the input polygon is analysed to determine the following extra parameters: width, steepness, and weir plane, and these are also fed into the assessment system. Once the input values are assigned to the nodes in the BN, the assessment system can then interrogate output BN nodes to retrieve the altered indicator values, which are then available to be displayed to the user.

The assessment system is designed to incorporate multiple assessment models at once and provide an overall assessment based on all connected models. The BN is integrated alongside a more traditional data and process driven model that examines the potential for hydro-electric power generation. This model, created in Excel, is integrated with the assessment system through COM automation. In a similar fashion to the BN integration, appropriate inputs are fed directly into the Excel model and cell values are available to read back to the assessment system.

Results of the multiple assessments can then be displayed either in a separate window, or within the visualisation, depending on suitability. The system outputs the results of assessments in HTML, which provides the basis for a highly configurable output to the user. The system displays the predicted states for indicator nodes in the Netica model and outputs one result of the micro-hydro model as proof of concept.

The 3D model generator is connected to the assessment system and, when a model is created, it forces an assessment to be made. The model generator compiles a list of all the variables needed and passes these, as required, to each analytical model in the assessment system. When inputs alter, it is the assessment system that is responsible for displaying the resultant indicator values to the user. This ensures that when a model is altered an up to date assessment is presented to the user. As the model generator issues the assessment, it can incorporate the results of the analysis in the resultant model. For instance, the model can be generated with a colour to display the level of weir "fun" derived from the BN to give visual feedback within the visualisation. An illustrative threshold value of 40% certainty being reached in either the "high" or "low" states results in the model being coloured green or red respectively, otherwise it is assumed to be in an intermediate state and coloured grey.

The various components of the system detailed in the previous section are functional, linked together within Simmetry 3d and respond interactively. Users can make weir modifications by changing parameters in a window that appears alongside the visualisation, as shown in Figure 47.

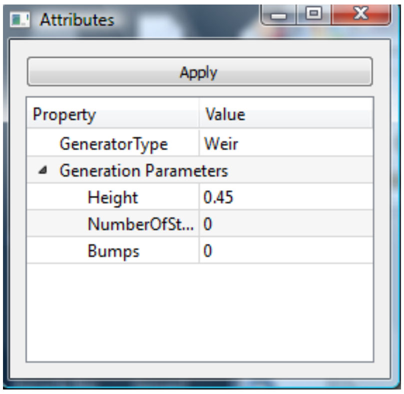
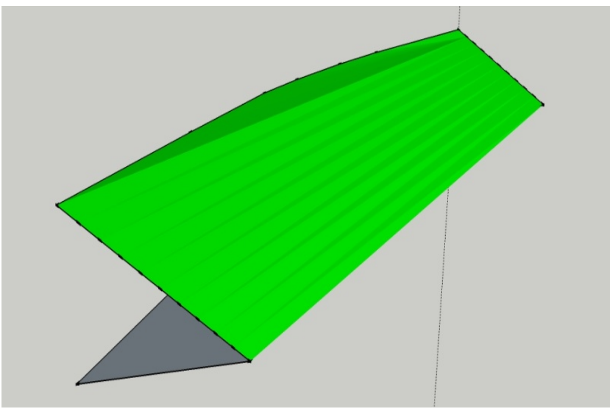


Figure 47: Weir modification parameter dialog

In Figure 48 two different weir modification options are visualised, separated for clarity from a larger landscape model. The first option shows a weir with a specified height of 1.4m, and the model shows a green colour to indicate a “high” level of “fun” for canoeists. The assessment window to the right shows the BN output for the overall quality of the stretch of river by the weir for canoeists, and the number of people the electricity generated by a micro-hydro scheme could provide for (based on the mean annual consumption in the UK). The second option shows a weir with a specified height of 0.4m and a stepped profile with the red colour indicating it offers a “low” level of “fun”. The second assessment shows little alteration to the river quality for canoeists (the BN may need further refinement), but a marked reduction in potential micro-hydro output.



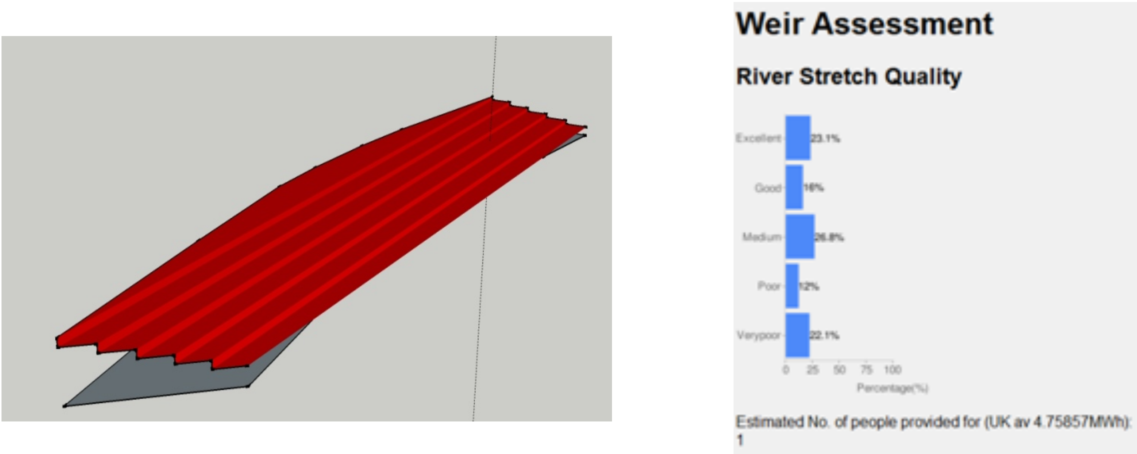


Figure 48: Two weir modification options for a weir modelled in 3D with their assessments

The weir modification system has also been placed into a larger manually created landscape model (Figure 49) that allows the landscape context to be understood as the weir is altered. This model is demonstrating the use of a more realistic textured surface for the weir rather than representing its "fun" factor.

Figure 49 - Interactive weir model in context within a larger existing landscape model

The result was that integration of the individual BN into an element of a 3D LIM was demonstrated to be possible and this led to the integration of a larger BN connected to the entire area of the landscape model.

6.2 URBAN RIVERSIDE SUSTAINABLE DESIGN BAYESIAN NETWORK

Having completed the successful integration of a model into a single element of the 3D landscape model, a larger BN (of Kumar et al [68]) that considered the landscape design of urban riverside areas in a holistic manner was then incorporated into the 3D LIM.

The aim of the larger BN was to capture expert knowledge about sustainable development of urban riverside areas. This model was constructed and provided by fellow researchers on the URSULA project. There were several types of input required by this BN in order for it to predict a set of output "indicator" values. These inputs could be defined as quantitative or qualitative. For example, the model required, amongst others, the total floor space and the amount of brownfield space in a design. The quantitative input values that mapped to existing land usage types or parameters were fairly trivial to integrate as they could be generated by the raster grid rendering technique already employed in the aforementioned geo-spatial assessments. This left other quantitative inputs that were not yet calculable and the more subjective input values, such as sensitivity of design for the area and how radical the design was. A user interface, shown in Figure 50, was created for changing the state of the BN inputs. So, having considered and discussed the 2D plan and 3D visualisation, the user could specify an appropriate value for each of these remaining inputs.

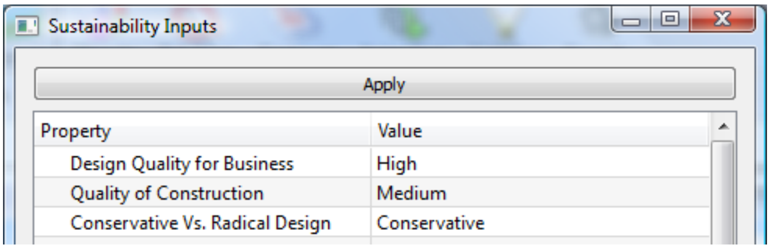


Figure 50 – User interface for altering input values to the sustainability BN

Once all the inputs had been configured for a design, the output of the BN was converted into a radar graph, which displayed the predicted state of the indicators. An example of this output is shown in Figure 51. An indicator would have three probabilities associated with it that helped ascertain the uncertainty associated with the predicted result. So, each indicator had a probability for a high, medium and low score. Using a formula described by Kumar et al [68], these three values were converted to a normalised linear scale between 0 and 1 for the radar plot, using Equation 1.

```
S = P(High) + ( P(Medium) / 2 )
```

where `P(x)` is the percentage probability of a state of an indicator

Equation 1 - Three state uncertainty value to normalised linear range

The radar plot was interactive, so a user could drill-down to see the underlying percentages, which can be seen on the right hand side of Figure 51. When the user switched between different versions in the user interface or edited the design, the system would keep the radar plot of the previous sustainability prediction, so the user could compare the results.

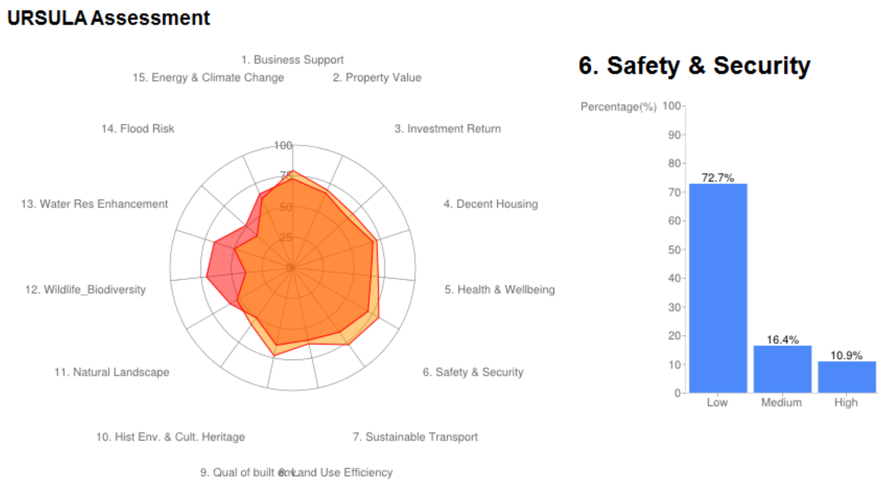


Figure 51 – Output of the sustainability BN

6.3 Discussion

BN represent an interesting method for incorporating expert knowledge about design into the 3D LIM. It can be concluded that a BN can be integrated into a 3D LIM. Given the rapid results that can be gleaned from a BN, this class of modelling seems to fit well with the real-time interactive design and feedback loop of the 3D LIM. The linked assessment works more efficiently when the values can be calculated from data held the 3D LIM, but given the qualitative nature of some BN inputs this may never be possible to fully automate. However, even with a BN with inputs that cannot be calculated by the 3D LIM, it is still possible for the user to utilise the landscape model as a visualisation tool. This could help users to discuss and judge the more subjective qualities of a design, manually configure the inputs to the BN and then receive feedback from an embedded BN.

With regard to the display of feedback to the user inside the 3D visualisation, the canoeist BN worked successfully and could provide feedback inside the 3D landscape model in the form of colour. However, it was not possible to use the sustainability BN in the same way, as the results from the BN are not spatial in nature. For further integrations with a 3D LIM it might be better to work at the individual element level and then aggregate into an overall assessment of the landscape design.

Both coloured models and radar plots suffer from the same problem, in that it is hard to feed back the uncertainty in the results to the user. The coloured model would suffer a “thresholding effect” such that the colour would only alter after a certain percentage in one of the three high, medium, low states was achieved. It may be possible to find other techniques for the display of the results, but this is outside the scope of this thesis and, as such, shall be left to others.

Chapter 7
COMPUTATIONALLY INTENSIVE MODELLING

There is a whole class of models that requires a great amount of computational resource to operate in real-time and be integrated into the interactive 3D LIM "edit and feedback" loop. However, this does not mean that they cannot be integrated, in some respect, with the 3D LIM. It could still be advantageous to the designer to be able to work with a "black box" model, even if feedback cannot be instantaneously provided on edits in the design.

So, consider a landscape proposal drawn as a 2D master plan that will require both an interactive 3D model for public participation purposes and a microclimate numeric simulation to examine Urban Heat Island (UHI) resilience. Both the inputs to microclimate numeric modelling and interactive 3D models can require large amounts of time to construct and tend to be undertaken as a manual process, which can lead to inherent problems. Procedures such as these can be error prone due to inaccurate translation of a 2D design plan into another system. If both a microclimate simulation and a 3D model of a proposal are to be constructed, it becomes a duplication of effort to create both the inputs to the microclimate modelling and the 3D visualisation. Design data becomes distributed in three places (2D plans, 3D model and microclimate simulation) and, as the designs evolve, keeping everything synchronized becomes increasingly difficult.

Intuitively, it would seem to be of benefit to re-use designs already held in a 3D LIM as an input to the microclimate models to predict the future performance of that design, rather than having to update the design in three places each time a design change is made. Given a spatial result set from any simulation run, it would also be possible to visualise this within the landscape model, presenting the simulation results in a 3D context. This workflow is shown in graphical form in Figure 52, where the changes to the 2D plan connected to the 3D LIM would update valid inputs to the linked model and then, when the results were available, be able to import the results of the simulation back into the 3D model.

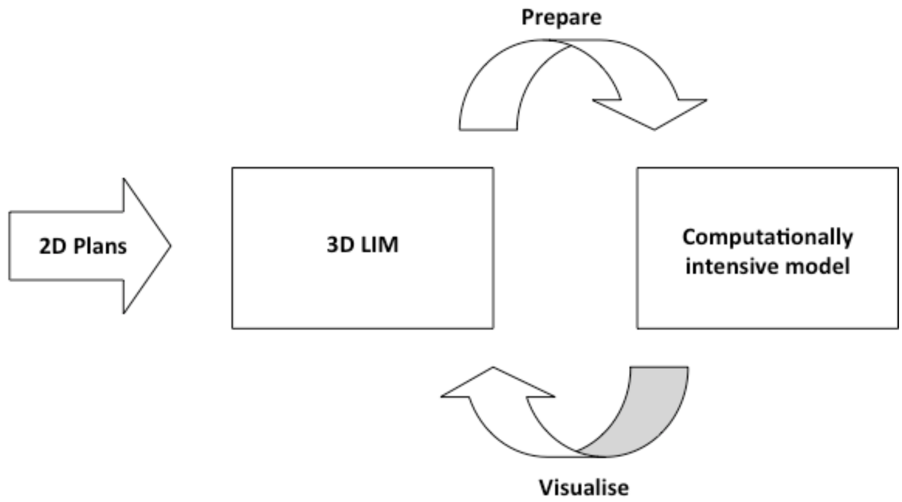


Figure 52 – Outline of the integration of computationally expensive model with a 3D LIM

This method leads to a removal of any human error in translation of a proposal into two distinct systems, potentially by different people. It also increases the speed at which alteration to plans can be analysed for performance. For those who find it hard to interpret plans [43], displaying the results within the 3D model may lead to easier cognitive understanding of those results. Workflows based on this methodology should enable the designer to work iteratively to consider further targeted changes to the 2D plans to improve UHI resilience.

To prove this offline linkage is possible, two existing models were connected to the 3D LIM prototype. The first is a model to predict microclimate performance of a design, detailed in Section 7.1 and the second is a flood model described in Section 7.2.

7.1 MICROCLIMATE MODELLING

Increasing urbanisation and a changing climate mean that consideration of the Urban Heat Island effect and methods to mitigate it are becoming a key concern in urban planning. Within planning frameworks, it is becoming accepted that adaption and resilience to climate change must be provided rather than simple focus on mitigation [94]. In a warming world the incorporation of microclimate simulation into 3D LIMs may well be essential.

7.1.1 ENVI-MET MICROCLIMATE MODEL

Envi-met version 3.1[26] BETA 5 was used for all the UHI modelling. This modelling software was deemed suitable because the input file formats were described in detail, allowing the linkage to a 3D model to be developed. The Envi-met model is a freeware numerical method that incorporates the interaction between atmosphere, soil system and vegetation in a single simulation tool. With a resolution of 0.5 to 1m in space and 10 seconds in time, it is used to study alterations to urban form in a variety of climates. The Envi-met software allows the generation of outputs at any time of the day for values of temperature, humidity, solar radiation, and a range of other variables at any point in the domain. This means patterns of cooling and identification of cooler and warmer areas can be carried out, although for decision making it is necessary to draw out a small part of the large amount of data available. For this purpose, Envi-met comes with its own visualisation tool, Leonardo, which allows visualisation in 2D and 3D of the results of a simulation run, but not in real-time.

As temperature calibration data was available for the Sheffield site that was modelled in the creation of the 3D LIM prototype, the same site was reused for the microclimate modelling. The 3D LIM prototype is capable of referencing LIDAR data held within Simmetry 3d to produce a 3D model with terrain. However, as Envi-met version 3 only uses a flat plane, it was decided not to use LIDAR in this case, simplifying the Envi-met data file generation process.

Given an existing 3D model, integration of Envi-met to the 3D LIM required two stages: creation of input data in Envi-met format and visualisation of the simulation results within the interactive 3D visualisation.

[26] www.envi-met.net

7.1.2 CREATION OF INPUT DATA TO ENVI-MET SIMULATION

Envi-met requires two files to run a simulation: an area description file and a configuration file. The configuration file contains all the parameters for running a simulation, such as total runtime and initial weather conditions. As this format does not include spatial information, a single file can be created and reused for a range of different site designs.

The input file is composed of several grids detailing the building heights, soil and vegetation states. These have to be input by hand and, in the case of multiple design proposals, this can become a time consuming process, especially as the grid size increases. The grids generated were 93 x 93, which means 8,649 cells per layer for each scenario to be categorised. As Envi-met can run grid sizes up to 250 x 250 (62,500 cells), this task soons become laborious, especially for multiple designs.

Therefore, instead of creating the input files by hand, the model held in the 3D LIM was used as a reference to construct the Envi-met input file automatically, thereby making it much easier to create multiple input files. To achieve this, the parametric construction of the 3D model was utilised to tag all individual elements of the 3D with appropriate key / value pairs, such as "*land usage = building*". At the least, each element is tagged with a land usage, but some objects would require further tagging, such as "*Building Height=10m*" for a building element in the model.

For the Envi-met export, the 3D LIM tagged rendering was repeated four times using four different element tags to construct the following grid layers: Land Usage; Height Data; Green Roofs and Building Base Heights. The data in these four grid layers were then composited together into the required Envi-met input file.

As this export process was performed by the GPU, it was completed in the four rendering passes of the model plus the set up time required on the main processor for each type of categorisation. This made it an economical operation in terms of time to complete. However, this speed advantage was reduced by the long periods that microclimate models take to run.

7.1.3 Visualisation of simulation results

Having generated the results from Envi-met, a technique for importing these results back into the 3D model was developed. This was done so that it was possible to display the results of the microclimate simulation within the context of the 3D model. Hence, areas in the 3D model would be falsely coloured with a more intense red value directly corresponding to the temperature from the microclimate simulation results.

This overlay was achieved by creating graphics card shaders. The implemented shaders provide for real-time manipulation of the simulation time of the microclimate results. Combining interactive simulation visualisation with the interactive view position provided by the 3D visualisation allows the viewer to control and view the data in a very flexible manner. In addition to this display of a single result, a second "differential" graphic shader program was developed that highlighted the areas of the model that were predicted to be cooler or hotter based on a user specified reference simulation and the simulation being compared.

The procedure for importing the results began with a manual extraction from the Envi-met result sets of the hourly results of surface temperatures for the 48 hours of simulation. Although the model generates a variety of outputs: air temperature; humidity; surface temperature and wind speed, only surface temperatures have been used in this instance. For each simulation, this step was repeated 48 times. Once the extraction was complete, an automated procedure converted the raw grid-based data into image files that could be used with the graphics shader. This involved a two pass process. Firstly, all the results were read to discover the maximum and minimum temperatures across all simulations. Secondly, all the hourly results were then encoded into an RGB scheme, using normalised values in the red component.

Once the image files were prepared a final automated import process was performed to create 3D textures on the graphics card that could be referenced by the shader. Each hourly result from a simulation run was placed into a separate layer of a 3D texture. It was then possible to interrogate the 3D texture from within the shader using a time parameter in the range of 0 to 1 that allowed access to hardware-interpolated results from the 3D texture. Regarding the implementation of the graphics shaders, the vertex program was a simple pass-through program that did not alter the 3D model and all the processing was done in a fragment shader with the 3D texture look ups providing colour values to overlay the model. Building walls were excluded from the colouring process using their normal value, so the 3D model context could still be perceived. A tolerance value could also be set which would only falsely colour over a certain percentage of the overall temperatures, meaning the user would see only the hottest percentage areas. In addition to this, the user could blend the false colouring in and out with the model colouring using an alpha blend value in the fragment shader.

Control of the simulation time by the user was implemented through a slider control in the user interface that updated a uniform *time* variable in the graphics shaders. This slider allows the user to move back and forth in real-time through the 48 hours of simulation time. However, it was also possible to create an animation of the results simply by automating the increment of this time variable.

7.1.4 Results

The case study of an area of Sheffield, UK, was used to develop the methodology. Two designs were exported from the 3D LIM prototype. The first was the current configuration of the Sheffield site based on the Mastermap data and the second was an alternative design based on a typical street layout (shown in Figure 7), generally consisting of hard urban materials but incorporating a 1.46% increase in the number of street trees aligning the main roads and in the new river side square. Buildings remain low, at a maximum of six storeys, and are stepped down to open areas and the riverside to prevent high wind speeds.

Before running an Envi-met simulation of the alternative design, validation of the current landscape state using an Envi-met input file generated from the 3D LIM was performed against known temperatures. After validation of the linkage and with the Envi-met model calibrated, the predicted effects of climate change were entered into Envi-met and simulations run on current and alternative design for years 2050 and 2080. For further information, these results and an examination of grid size sensitivity in Envi-met have been published by Gill et al [95].

Using the developed data import and graphic shaders, it was possible to create an interactive, real-time display of microclimate surface temperatures and differentials overlaid on to the 3D model. For example, on the left image of Figure 53, surface temperatures for the 2080 simulation of the alternative design are displayed using more intense red (lighter) values for hotter surface areas with an 85% blend value of temperature colouring to the existing model colour. The right of Figure 53 shows a snapshot in time from a visualisation of the alternative design in 2080 with shading used to show the temperature difference between this scenario and the calibration temperatures. The hotter areas are shown in red (darker areas) and green (lighter areas) is displayed where it is cooler. Although some larger areas are cooler there are "hot spots" that result in warmer temperatures in the alternative scenario. This highlights the advantage of visualising the spatial variation in temperature; designs can then be adapted to provide further mitigation in the warmer areas.

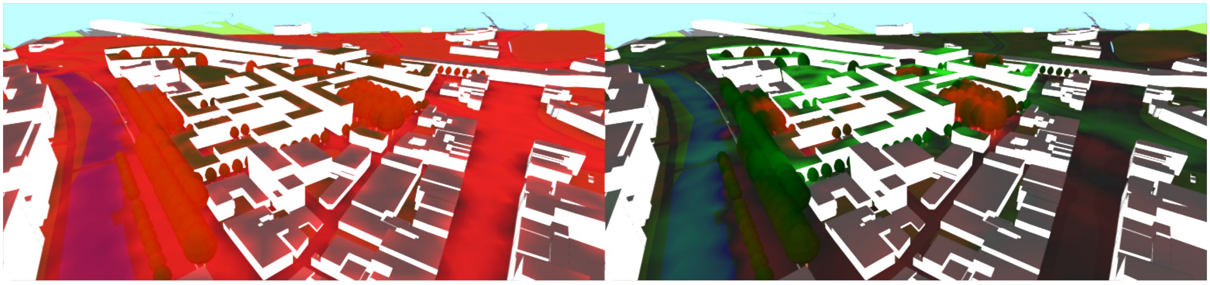


Figure 53 - (left) graphics shader showing 2080 results, (right) differential graphics shader showing areas of heating and cooling between 2050 and 2080 simulations, both with 85% blend

Given these results, it can be deemed that graphics card shaders are suitable for representing real-time display of Envi-met surface temperatures within an interactive 3D visualisation. As the Envi-met results detailed above are for the entire modelled area, the shader programs overlay the data across the entire area of 3D model, but it was demonstrated that with extra calculations in the shader programs it is possible to overlay an arbitrary rectangular area on to the 3D model. This would be useful if a smaller area than the entire site was needed to be modelled at a higher resolution.

Currently, the graphics shaders are only able to visualise the Envi-met surface temperatures or one layer of atmospheric data at a time. Chow and Brazel [96] found that their model under-predicted temperatures, particularly close to the surface, so it would be a good extension to the system to be able to visualise the entire modelled atmospheric volume at once. It would be of interest also to examine how well simulations presented in this manner compared to standard techniques of coloured grids or plans. Envi-met version 3 employs only planar terrain definitions, whereas Envi-met promises better 3D modelling in version 4. When this functionality is released, the tagged rendering function in Simmetry 3d would need to be extended to render slices of the model at a certain height. This way a 3D gridded volume could be generated from the procedurally generated 3D geometric model and thus used to define the Envi-met input files.

7.2 FLOOD MODELLING

Flooding related to climate change is another important issue that could already be affecting communities in Western Europe [97]. In populated areas flooding can have significant effects on property prices and insurance, the physical and emotional safety of inhabitants and can deposit all manner of pollution into an area. Certainly in the UK, where there is pressure on suitable land for new building, housing construction schemes are often proposed in areas with some level of flood risk. As such, it is important to consider the resilience of future landscape designs to both pluvial and fluvial inundation for sustainable management of landscapes. To this end, there are a variety of 1D and 2D flood models available in academic and commercial use today, such as LISFLOOD-FP[27] and TUFLOW[28]. Burch et al [62] introduced computer generated 3D imagery showing the effects of a range of predicted sea level flooding induced by different climate change and management scenarios into a collaborative planning process. Participants in the process found the provided images credible and the imagery was found to promote communication between participants. Thus, integration of a flood model with a 3D LIM would seem beneficial if designers can automatically visualise the flooding resilience for their landscape designs. Thus, given the spatial nature of a 2D flood model over that of node based 1D modelling, it was decided to examine the possibility of integrating an existing linked 2D fluvial flood model with the 3D LIM.

[27] http://www.bris.ac.uk/geography/research/hydrology/models/lisflood

[28] http://www.tuflow.com

7.2.1 *ISIS MODEL*

A 2D flooding simulation (1:100 year plus climate change flood return period) had already been run for a flood mitigation proposal for the area of Sheffield used in the microclimate case study [98]. This model was built, by a colleague, in ISIS[29] software and employed high resolution LIDAR (0.5m samples ± 0.5m height error) to define the terrain. The site was susceptible to flooding and a flood channel was proposed as a possible flood defence for the area (see Figure 7 for the flood channel plan detail). To predict effectiveness of this design, the flood model was deployed. This was achieved by manually sculpting the existing LIDAR for the area raster terrain tools in Simmetry 3d to create the flood relief channel in the terrain model. The user interface of ISIS was used to introduce further flood defence walls to the proposal. The model was run and produced a simulation of water depth and flow velocities.

7.2.2 *INTEGRATION WITH 3D LIM*

An existing 3D landscape model for the flood channel had been produced for the purpose of visualising the flood channel proposal. At the time, the flood channel model had not been entered into the 3D LIM, but a model that been constructed manually by another colleague in Simmetry 3d was available. This model was based on the same LIDAR data used in the original model, but the terrain model had been corrected for errors using advanced region based terrain editing tools still under development in Simmetry 3d. As a consequence, the terrain levels in the manually modelled version were more accurate than the sculpted version, especially at the mouth of the flood channel where 3D meshes of gabions had also been placed.

The 3D LIM plugin inside of Simmetry 3d was extended to sample the model at any specified resolution to obtain the height of the model at each sample point. To match the existing ISIS model, the model was sampled at 0.5m x 0.5m intervals. The resulting grid of heights was then saved in an ISIS supported GIS format, effectively producing a "LIDAR" trace of the 3D landscape model held in

[29] http://www.halcrow.com/isis/

Simmetry 3d. This height data respected the heights of any visible 3D models placed on to the terrain surface and, therefore, captured the heights of the gabions in the output. This method allowed the designer to visualise the flood defence structures in 3D rather than being forced to add them as polylines to a 2D plan, although the features captured were related to the resolution of output height grid. In other words, the resolution of the grid must be fine enough to sample the smallest of features that need to be captured.

The point sampling of heights using one thread on a CPU proved time-consuming and, following discussion with a Simmetry 3d developer, a Simmetry 3d API function was created that provided a depth-based render of the loaded 3D model using the GPU, significantly increasing the speed of the model height data export.

Another optional input to ISIS that can be specified is a grid of friction coefficients for the modelled domain. Eventually, the flood channel design was imported into the 3D LIM prototype. Using the 3D LIM prototype and the tagged based rendering, it was possible to generate a friction coefficient grid based on land use type, which alongside high resolution terrain data can have significant effects on flood simulations [99, p. 31].

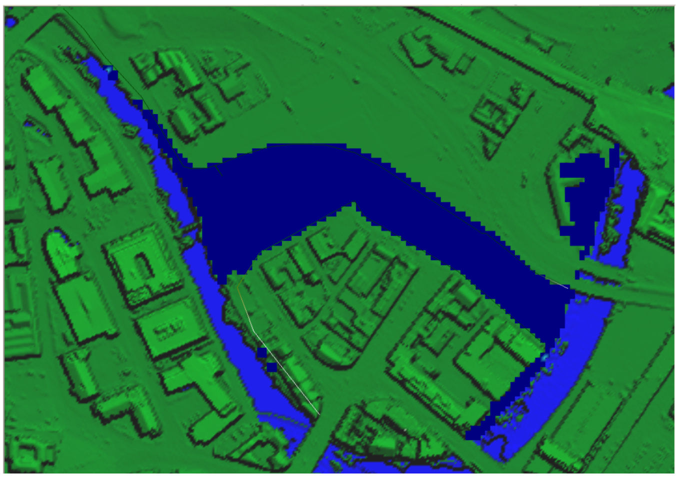


Figure 54 – Output from ISIS showing simulation of a flood channel proposal

Often the results of flood modelling are shown as 2D plans, as can be seen in the output from the original ISIS flood channel simulation in Figure 54. However, it was possible to import the flood simulation results back into the 3D LIM. To perform this task, a custom import function for reading the simulation results into the 3D landscape model in Simmetry 3d was created. The water height results of an ISIS simulation were exported at regular time intervals as ASCII grid files, which could then be automatically added to the Simmetry 3d model as 3D objects within the scene graph of the model. An animation that showed one of these objects per timeframe was created, which resulted in a time sequence animation of the flood event within the 3D model. Unfortunately, there is no API to a Simmetry 3d animation, so these animation sequences had to be constructed by hand.

Once the water height objects were present and the animation created, it was possible to interactively move around the 3D landscape model whilst the flooding animation looped. For example, this would allow the user to position themselves at eye height to watch the inundation event in the flood channel.

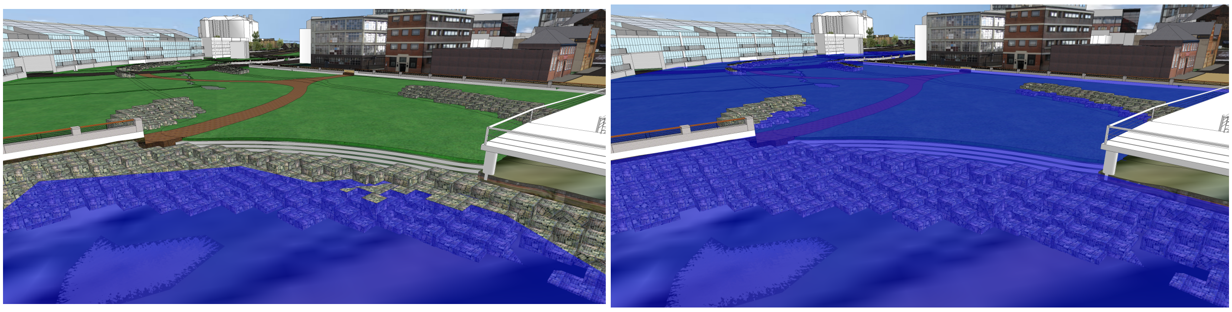


Figure 55 – ISIS simulation results in Simmetry 3d model, showing before and after breach of flood channel defences

It was also possible to visualise wading risk based on the degree of hazard defined by the Australian best practice guide [100, p. 71]. This required the pre-calculation of wading risk from the depth and velocity data produced by ISIS. Wading risk at each grid point in the simulation was colour coded and then stored in a texture file that could then be referenced for pixel colouring by a graphical fragment shader program. The calculation of wading risk was performed as part of the import process in the 3D LIM and was automatically done for the user. The wading risk shader could alter the colour of the water objects based on the wading risk (Figure 56 - more red means greater risk) and because the shader performs in real-time, this visualisation could be toggled on and off interactively.

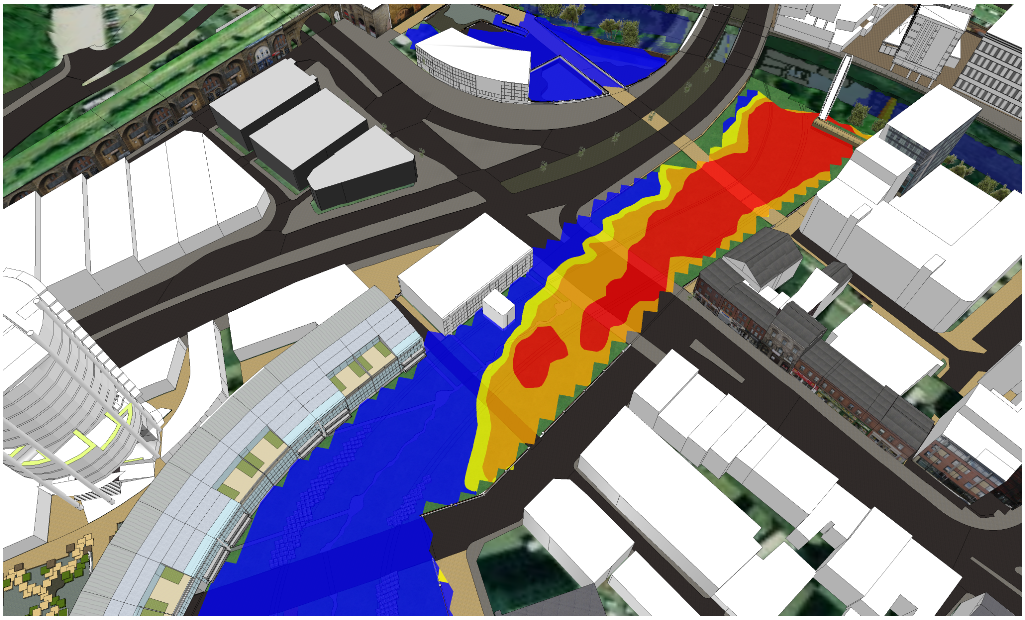


Figure 56 - Visualisation of wading risk in the flood relief channel using graphics shader program

7.2.3 Results

The export of the height data was possible using either the CPU or GPU method, but as the exported grid size increased, the GPU method with its multi-processor capabilities was significantly quicker, as can be seen in Figure 57.

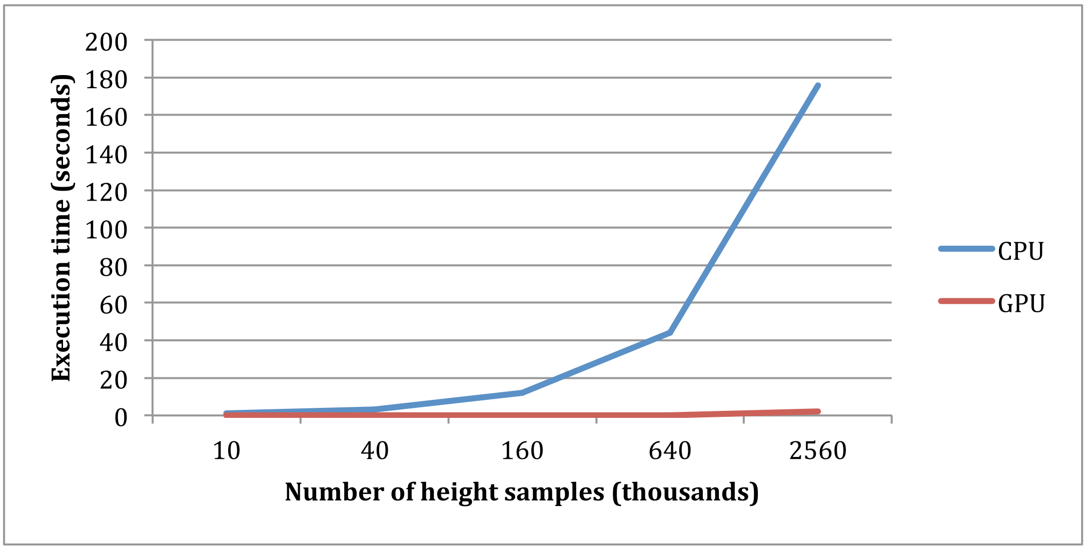


Figure 57 - Execution time against height samples in height export

It proved possible to use the 3D LIDAR trace export from the 3D landscape model within the ISIS flood model to generate a successful simulation run. An exported friction grid was not used in the simulation, so that the results from the two simulation runs would be comparable. Figure 58 shows water depth over time at a single grid point at the mouth of the flood relief channel. It can be seen, when analysing this graph, that the difference in the terrain input file has significant effect on the results of the flooding simulation. The inundation of the flood channel occurs much later in the simulation with the original LIDAR and the water depth is increased overall in the 3D LIM height data export.

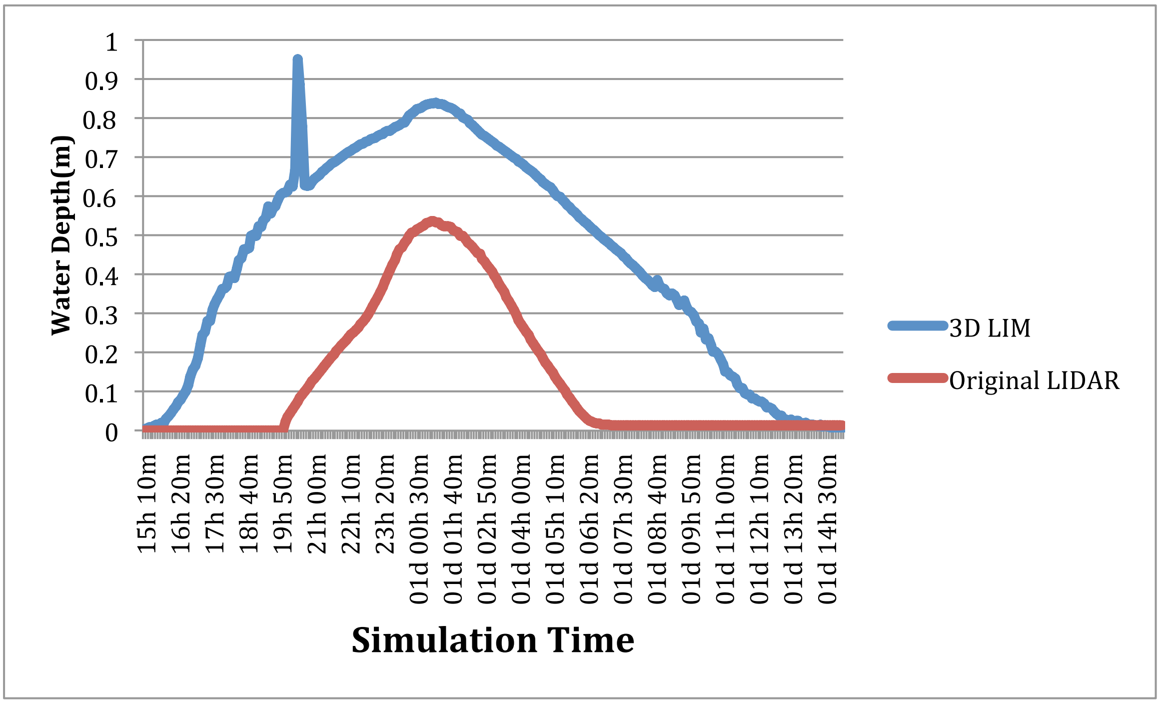


Figure 58 - Water depth at point sample in mouth of flood channel

It also proved possible to export from ISIS at hourly intervals from the simulation results and then provide an import into the 3D LIM, which asked the user to only select a directory containing the processed result files. The construction of the animations by hand was time consuming and error-prone but, if this shortcoming was to be addressed, it would make the ISIS integration loop much more user friendly.

7.3 DISCUSSION

This chapter has explored the integration of two distinct computationally intensive models with the 3D LIM prototype. It has been shown that data held in the editable 3D landscape model can be re-used in separate simulations and the results of these simulations visualised in the context of the 3D landscape. These integrations suggest that the tagged render method lends itself to integration with simulations that are based on discrete grids.

Alongside the tagging system, it seems the height data held in the 3D landscape can also be of importance. Envi-met is being developed to take account of terrain and high definition remote sensing terrain data is increasingly being used for flood modelling [99]. However, it remains difficult to acquire accurate terrain models. Remote sensing techniques, such as LIDAR, provide high-resolution data, but may contain significant noise. This noise and the difficulties faced in accurately manipulating the height data will almost certainly lead to inaccuracies in simulations that require terrain models, such as can be seen with the significant differences in the two flooding results. It has been shown in this chapter that if an existing digital 3D landscape model with accurate terrain can be modelled, then the information can be re-used in both flooding and microclimate simulations. Lameiras et al state that digital interfaces to terrain modification remain difficult to use for designers [101]. Perhaps an extension of the 3D LIM parametric regions to terrain modification could be one method that would allow both easier and more accurate manipulation of terrain.

The integration methodology presented revolves around the ability to move information from one system to another distinct system and vice versa. This was in the most part achievable, but the data held in the Envi-met simulation results was locked within proprietary file formats. Envi-met comes with its own visualisation tools, but it would be advantageous to allow easy access to the resultant simulation data through a programmable interface or through export to a standard well-known format. The manual extraction process from Envi-met remains the slowest part of that integration and was error-prone due to the number of steps required for each hourly result extraction. It would be much improved if an automatic exporter could be developed that read the Envi-met results files. Exporting data from the ISIS model proved a more simple process, but some manual processing was still required to construct the animated flood sequences. This could be resolved relatively easily, however, by extending the Simmetry 3d API to include animation construction.

Moving forward, it would seem useful to link multiple simulations in the way Envi-met and ISIS have been coupled if, and only if, there is "freedom of information" between systems. CityGML is a standard that allows transfer of 3D city models between systems and the EC INSPIRE standard is an attempt to define an interoperable "European spatial data infrastructure" (p. 25) based more on 2D with 3D extensions [102]. As an alternative to such interoperable data standards, initiatives that allow programmatic links between different simulations, such as the OpenMI [103] initiative, might also provide a productive avenue. Such data exchange may become even more useful if the 3D LIM were to be integrated as a simulation controller, coordinating time steps and the exchange of data at each time step between integrated simulations. Therefore, the more computationally intensive modelling systems that adopt these open standards the easier it will be to move away from silos of data trapped in only one system.

Finally, to allow more design options to be analysed, methods should be sought not only for reducing the time taken to create model inputs, but also for reducing the run times of computationally intensive simulations. Given the increase in simulations based on GPU that have seen reduced completion time from hours to seconds due to the computational power available on a single GPU [103], it is also possible that the calculations performed by the Envi-met and ISIS systems could benefit from such acceleration. Not only could this reduce the time taken to analyse the UHI and flooding performance of a design proposal, but running the simulation on the GPU would also make it possible to visualise the results as the computation is taking place, both self evidently advantageous.

Chapter 8
AGENT BASED PEDESTRIAN MODELLING

Landscapes are populated by humans and visualisations of landscape should regard them as vital elements. In static imagery, it is simple to digitally insert photographs into landscape scenes. However, in order to maintain the simulation of reality in a virtual 3D environment, these virtual humans need to behave and move in a manner that will not draw attention from the viewer. Moving beyond visualisation and with regard to landscape design, Joh et al highlight how the configuration of urban form has an effect on pedestrian walking behaviours, which should be considered when designing sustainable future urban areas that may minimise car usage [104]. Furthermore, pedestrian simulations of predicted human behaviour may give a designer insight into likely usage patterns in normal and emergency scenarios, which can be important for densely populated urban environments.

Thus, the reasons to integrate pedestrian models with a 3D LIM are twofold. Firstly, crowds of pedestrians serve to fill up the empty spaces often associated with interactive 3D landscape visualisation, which may provide an altered viewing experience of the design. Secondly, the chance to rapidly predict human behaviour in response to a change in landscape design with visual feedback is manifestly opportune.

Pedestrian simulation techniques can be broken into two categories, macroscopic and microscopic. Papadimitriou et al [105] present a comprehensive review of urban pedestrian modelling techniques and suggest that an increasingly applied approach to microscopic pedestrian simulation is agent based modelling, which treats each pedestrian as a separate algorithmic unit. These agent based pedestrian models are often based on the flocking behaviour of Reynolds [39] and the social forces model of Helbing et al [40]. One of the problems that agent based pedestrian models must deal with is to provide journeys for each pedestrian and navigation information that allows individual agents to complete these. Agent based pedestrian simulations usually employ one or a combination of pre-defined paths [106], cellular automata [107], or the aforementioned force based methods to provide navigation. Each agent in a simulation is given a goal position to reach and the pre-defined paths, automata rules, or force calculation determine how each agent moves toward that goal.

It is possible to automate the procedure of detecting pedestrian routes within an area of landscape using automatic procedures to detect pedestrian areas within a map [108]. Once the areas available for walking upon are determined, such pedestrian areas can be turned into an input to the pedestrian model in the form of navigation reference grids or as waypoints for path finding algorithms.

Offloading model computation to a massively-parallel processor, such as the GPU, can lead to lower simulation run times and also makes visualisation of the simulation easier as the resultant data is already resident on the graphics hardware [109]. Karmakharm et al developed a GPU based agent model for pedestrian simulation based on a combination of Reynolds and Helbing's algorithms, which offered the ability to simulate and visualise tens of thousands of pedestrian agents in an urban environment faster than real-time using pre-calculated vector fields for defining navigable areas [110].

Another important element of landscapes, especially urban environments, is automotive traffic. Regarding how humans interact with traffic, Ishaque et al [111] review several studies which highlight the spatial non-compliance of pedestrians with existing pedestrian crossings. They suggest a pedestrian will cross a street based on a combination of perceived risk and the pedestrian's value of time and appreciation of their own capabilities. Agent based pedestrian simulations should take account of such behaviour.

8.1 COMBINED GPU PEDESTRIAN AND TRAFFIC MODEL

Thus, it was decided to attempt to integrate a design held in the 3D LIM prototype with a real-time pedestrian model that was responsive to traffic movements, since these elements would provide 3D landscape visualisations with dynamic elements present. This would take three steps to complete. Firstly, an existing pedestrian model was refined to contain dynamic obstacle agents that would exercise control over the movement of pedestrian agents. Secondly, vehicular agents were then added in a similar manner to the pedestrian model. Finally, a 3D landscape model was exported from the 3D LIM to provide an editable environment for the pedestrian simulation.

8.1.1 PEDESTRIAN MODEL

An existing pedestrian simulation developed by Karmakharm et al that used the GPU agent based modelling framework, FLAMEGPU [109] was available for integration to the 3D LIM. FLAMEGPU is an agent based modelling abstraction layer, which generates NVidia CUDA[30] code that can be executed on the GPU. This force based simulation worked on the principle that each pedestrian agent is subject to multiple forces at any one point in the simulation. These forces consist of an overall force towards the goal of the agent, together with a social force with other agents within the vicinity, and an obstacle avoidance term. The sum of these forces defines the direction of movement of the agent at each time step, as shown in Equation 2.

$$F(a) = F(goal) + \sum_{i=0;i\neq a}^{n} F(Social(a,i)) + \sum_{j=0}^{m} F(Obstacle(a,j))$$

where:

$F(a)$ = Force on agent *a*

F(goal) = Force toward goal

F(Social(a,i)) = Social force between agent *a* and agent *i*

n = Number of pedestrian agents close enough to agent *a* to cause a potential collision

F(Obstacle(a,j)) = Force between agent *a* and obstacle *j*

m = Number of obstacles close enough to agent *a* to cause a potential collision

Equation 2 – force model for an agent at each simulation step

The social force term includes comfort zones, intimacy and impending collisions with other agents. This model used a pre-calculated force vector field to steer the agents away from buildings. The

[30] http://www.nvidia.com/object/cuda_home_new.html

vectors are computed prior to the simulation running and this provides an efficient method for moving agents with a GPU texture lookup to reference necessary navigation data. The downside of this method is that the environment must be divided into equal sized chunks and is constant for the entire simulation. If the need to represent a large area is required, the size of the vector field must increase to keep the chunk size small enough to represent all features in the environment. This requirement can be a problem when considering large urban environments, as memory on the GPU is often more limited resource in comparison to the computational power available. These schemes may also be wasteful for environments with large open areas and these issues also relate to cellular automata based solutions. Additionally, the existing pre-calculated force based method cannot handle dynamic movement of obstacles.

However, a solution to this problem would be to add agents into the simulation that define the vector field mathematically and use all such agents within the obstacle term at each simulation step. It would add repulsive and attractive forces into the simulation, analogous to how the agent is repulsed using the social force. Moreover, extending this dynamic force calculation to the built form in the simulation could also be advantageous over the pre-calculation of the environment, as it would allow pedestrian pathways to be altered within the simulation. The disadvantage is that this would require more computation per simulation step, but considering the GPU has a large amount of computational resource available, this may be a valid trade-off for the added flexibility in the modelling system.

Thus, the chosen solution to the force based simulation would be to mathematically construct a navigation vector field for each agent at each simulation step. This could be achieved by defining ***attractor*** and ***repulsor force agents*** that could be placed into the simulation environment. Each pedestrian agent would then be able calculate their obstacle avoidance term from the repulsor agents surrounding it, as shown in Figure 59.

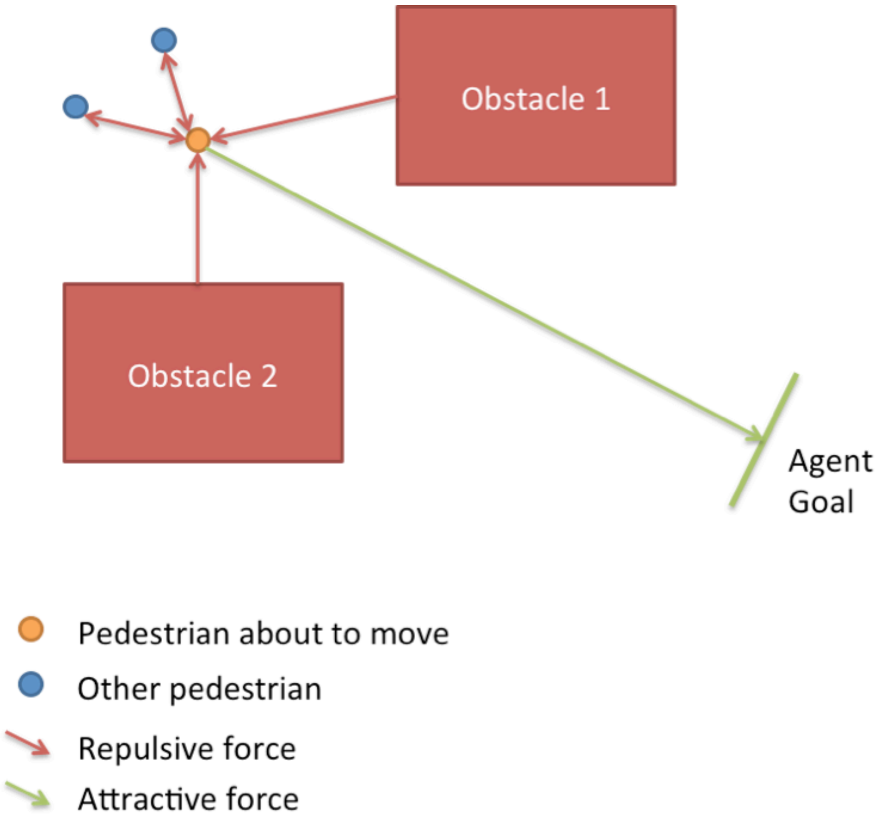


Figure 59 – Repulsive forces acting on a pedestrian agent

By defining repulsive forces for obstacles, the pre-requisite for a grid data structure is removed. This allows detail to be injected into the simulation where it is needed, saving memory for large open areas where pedestrians are free to roam. It also provides the possibility for making dynamic alterations to the simulation through the addition, alteration and removal of attractor and repulsor agents. For example, an earthquake could be represented as a highly repulsive force agent, repelling pedestrians from its increasing zone of influence.

Repulsor agents were designed to be linear and defined by two points (a start and an end) and also had a strength attribute to define the effective zone of repulsion around it. An attractor agent would simply have a negative strength attribute. These force agents defined their area of effect using the strength attributes as a parameter to a configurable exponential fall-off. This is useful for defining different types of repulsor. For example, a building wall need only repulse over a relatively short range (0.45m according to Willis et al [112]), whereas an earthquake event would affect a much larger area.

FLAMEGPU provides inter-agent messaging whereby each agent type was required to publish its location and repulsive force so that each agent could process the messages relevant to them from other agents. The message passing stages occurred first so that with the processing occurring later in one FLAMEGPU function for each agent type. The functions were as follows:

```
BroadcastPedestrianLocation();
BroadcastAttractorLocation();
ProcessAttractors();
MovePedestrians();
```

At each simulation step, each pedestrian agent would broadcast its location and then each attractor agent would broadcast its start and end positions and strength. In ProcessAttractors(), each pedestrian would then iterate through all attractor messages in the FLAMEGPU queue and sum the vector forces acting upon it from each repulsor, where magnitude is based on the distance from itself to the repulsor, calculated using line intersections. This repulsion vector was then stored as a property of the agent. Finally, a new position and direction was calculated for each pedestrian agent in MovePedestrians() using the repulsion vector, the social force vector and the goal vector.

For efficiency, the spatial sub-division of messages in FLAMEGPU was used to cull far off repulsors messages from having to be processed, minimizing the number of messages each agent needed to process.

The pedestrian agents were introduced into the simulation using manually defined emitter and exit pairings. An emitter would generate pedestrians in the simulation at a certain rate per minute and each pedestrian agent placed into the simulation would have their destination goal set to the matching exit for that emitter. It was possible to remove an exit and the agents heading for that exit were remapped to another randomly chosen exit. A pedestrian would be removed from the simulation once they had moved within a certain distance of their goal.

8.1.2 Traffic Model

A simple traffic model was implemented that defined a road network which vehicle agents would use to travel along. The road network was defined using a graph of node pairings. The first node represents a starting position and the second a goal position for a car starting from the first node. Every node can generate vehicles into the simulation at a given emission rate per minute. Each generated vehicle is assigned the corresponding goal node position and will travel in a linear fashion directly to that goal. Once a goal node is reached, it looks up a subsequent goal from the car path network data structure stored on the GPU, or is removed from the simulation, if there is no further goal to move to. A node could also define multiple node pairings representing a junction from which a vehicle would randomly select a goal node. Each vehicle would respect vehicles ahead of it using the Gipps car-following equation [113].

One method to incorporate the traffic into this existing simulation would be to introduce vehicles within the obstacle term. So, given the ability in the pedestrian simulation to define a dynamic obstacle field across the simulation, traffic agents were added as mobile repulsors to pedestrian agents. This method allows pedestrians to move freely toward their goals, but to take account of the movement of traffic as it passes close to them, as shown in Figure 60.

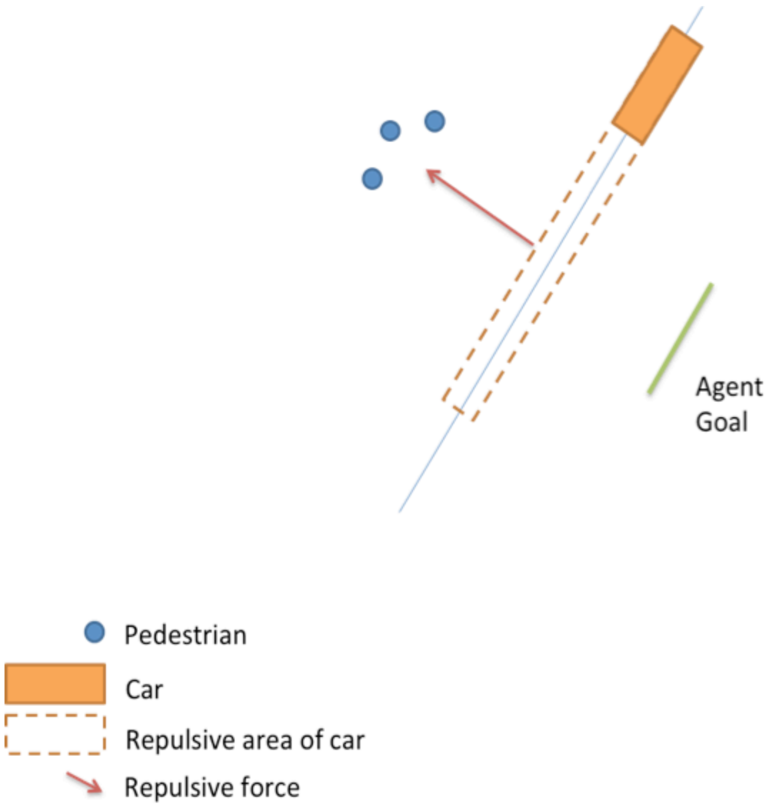


Figure 60 – A car agent as a repulsor force agent for pedestrians

The length of the repulsive area of a car is based on the speed of the vehicle. This means that when the vehicle is stationary it allows pedestrian agents to move across its path, and attempts to simulate a pedestrian's perceived risk and gap acceptance, identified by Ishaque et al [111]. The model was set up so that pedestrians were responsive to vehicles and vehicles to other vehicles, but not vice versa. The message passing and processing scheme was extended to the following:

```
BroadcastPedestrianLocation();
BroadcastAttractorLocation();
BroadcastCarAttractorLocation();
BroadcastCarLocation();
ProcessAttractors();
ProcessCarAttractors();
MovePedestrians();
MoveCar();
```

The BroadcastCarAttractor() function would add an extra message queue of repulsors and the extra vehicular repulsion vectors were added to each pedestrians agent's repulsor vector in ProcessCarAttactors() function. The BroadcastCarLocation() and MoveCar() functions were used to implement message passing of car agent locations for the Gipps car following scheme. No collision detection was implemented for either vehicles or pedestrians.

8.2 INTEGRATION WITH THE 3D LIM

The existing FLAMEGPU based pedestrian model was implemented within a custom C++ GUI (ACVEngine[31]) that used OpenGL for 3D rendering. It was possible using the GUI to manually position pedestrian emitters and exits and this manual interface was extended to allow manual positioning of repulsors and attractors.

The 3D LIM prototype holds a 2D land usage model in Sketchup format with the regions of the map tagged by attributes (defining whether a region is available to be walked upon) and a procedurally generated 3D model. A custom export function from Sketchup was created to categorise each line in the building regions of the 2D plan as a repulsor (start position, end position and strength) and these were imported to the ACVEngine simulation system via a file holding the repulsor data. This workflow removed any need to manually draw or automatically detect non-walkable areas.

Next, the procedurally generated 3D model was exported to the ACVEngine by converting the Sketchup 3D model into a file format that the ACVEngine could read. The final stage needed to set

[31] ACVEngine 2011 created by Twin Karmakharm [twin@dcs.shef.ac.uk]. Unpublished.

up the model was to manually draw in the road network and pedestrian entrances and exits within the ACVEngine GUI.

8.3 RESULTS

The 3D LIM system was used to import an urban area approximately one square kilometre in size from Ordnance Survey data. As can be seen in Figure 61, the yellow areas in the land usage model represent building footprints. The building wall repulsors were then successfully exported to the ACVEngine, shown in Figure 62. The 3D model was then exported from Sketchup into ACVEngine.

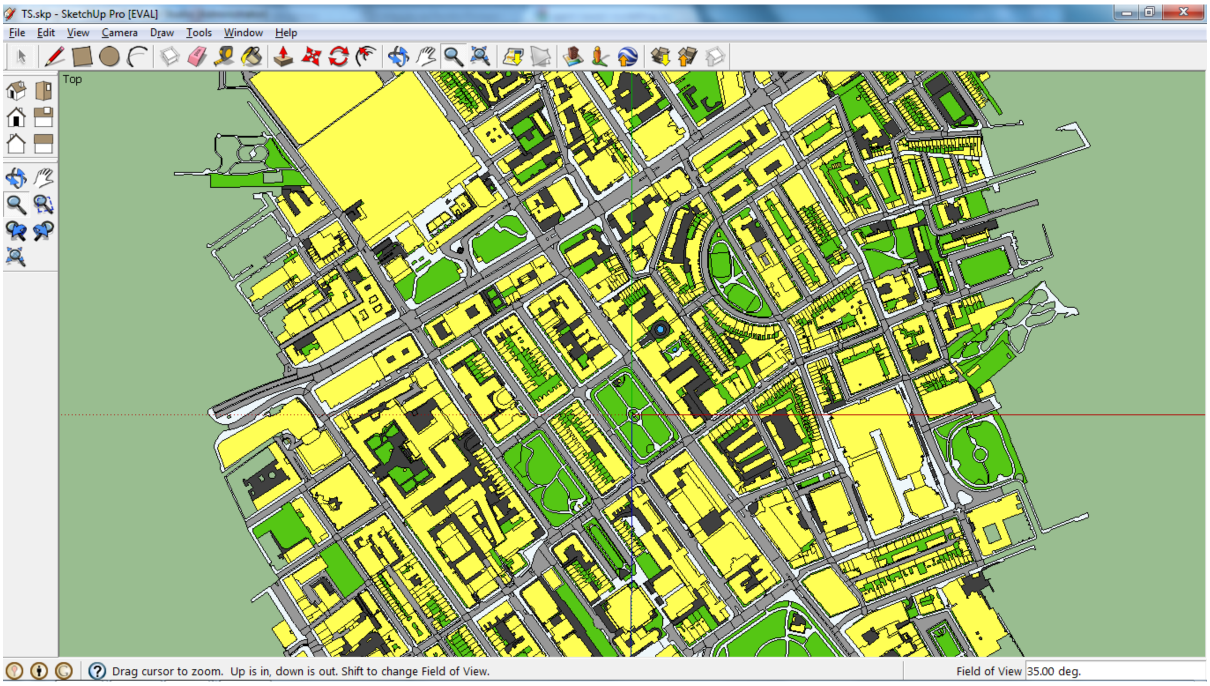


Figure 61 – Landscape semantic defining repulsors

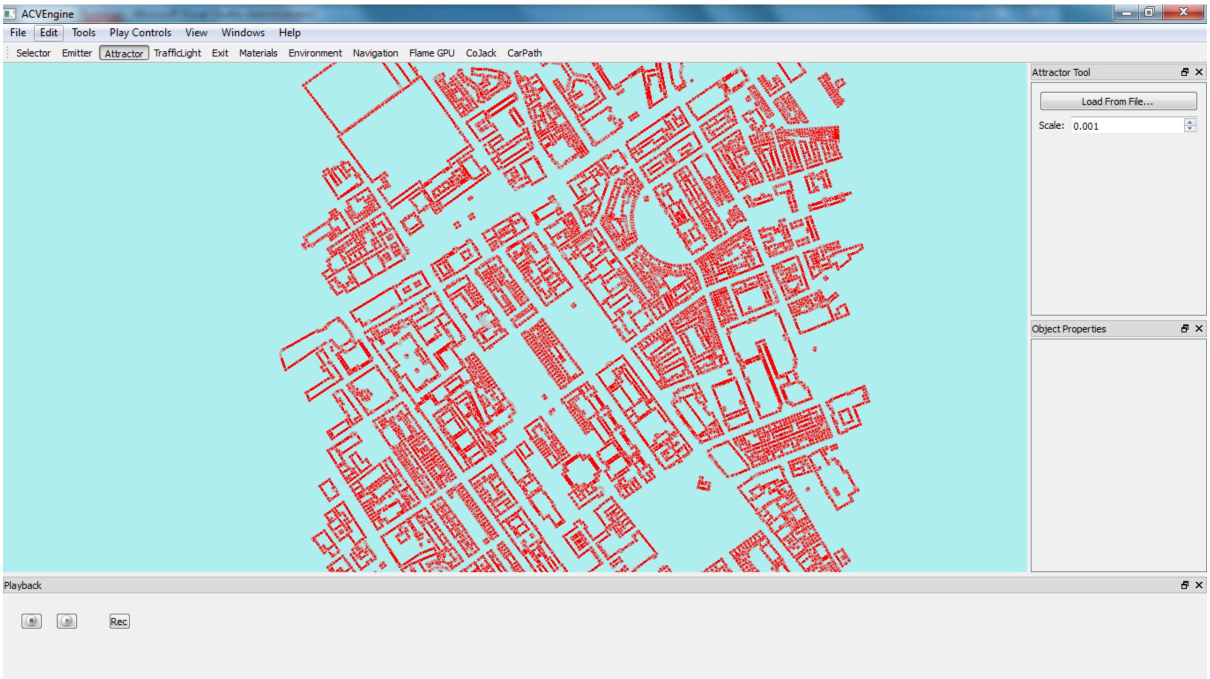


Figure 62 – ACVEngine system with building repulsors loaded

The export procedure from the 3D LIM was a straightforward procedure that took less than 8 hours to gather the map data, corresponding LIDAR, load this into the 3D LIM prototype and finally convert this to ACVEngine formats. However, the manual input of the road network and pedestrian entrances and exits took a significant amount of time and only provided a basic test of the road network and pedestrian ingress / egress systems.

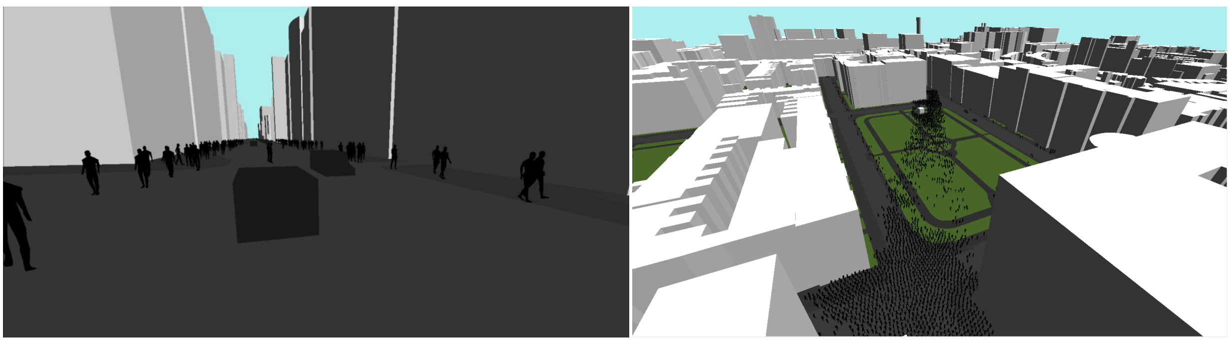


Figure 63 - Views of the pedestrian and traffic simulation in ACVEngine

It was possible to create interactive eye level walk-throughs with basic car and pedestrian models, which can be seen the sample screenshots taken of ACVEngine in Figure 63. Using a 2.3GHz Intel i7 with 8Gb RAM and NVidia GT650M 1Gb GPU (384 CUDA cores), it was possible simulate and visualise faster than real time 23,989 repulsors, over 4300 pedestrians and 1470 cars, as depicted in Figure 63. The upper limits of the simulation have not yet been tested. The resultant visualisations have two dynamic simulation elements, traffic and pedestrians. These agents interact with each other to provide emergent behaviour. For example, pedestrian agents in the simulation may choose to cross roads at any point, rather than at pre-defined crossing points, but will be stopped when traffic is passing.

Allowing pedestrian agents to move freely within a landscape provides a simulation with more emergent behaviour than ones with pre-defined route choice simulations. However, the force-based model was sensitive to the balancing of forces and pedestrians can become "stuck". If the modelled area is pictured in terms of a dynamically constructed potential field (such as described by Gloor et al [114]), there will be an overall descent towards the goal position, but repulsors can create local minima where forces cancel each other out. If a pedestrian agent enters one of these areas, they will become trapped. This happens generally to more isolated individuals in the simulation as social forces often provide an extra influence to move trapped individuals out of minima. One method found to deal with this is to manually define an attractor force agent in the simulation that will help to "pull" agents out of the localised minima. This means that the pedestrian agent must remember the attractor, so that its effect is ignored after it is reached to allow the agent to progress towards a goal. Another method that was found to reduce this behaviour is to simplify the movement of pedestrians, so that pedestrians do not meet any local minima, e.g. they are simply set to walk from one end of a street to the other. This works for visualisation purposes, but may prove problematic for simulating complex pedestrian behaviours.

The simulation did have certain limitations. Firstly, pedestrian agents are represented by identical 3D models in the visualisations and this is the same for vehicles. Pedestrian agents under the influence of several repulsors could exhibit rapid oscillation in direction, which may adversely draw the attention of the viewer. Also, in order to get successful pedestrian movement, it was necessary to apply weighting to the different terms in the pedestrian movement equation and balancing these seems to be a manual task. The simulation it should be noted takes no account of terrain. In addition, the car following model is very basic with no lane changing or junction priorities, making complex vehicular behaviour impossible to model.

8.4 DISCUSSION

This integration of a landscape design held in a 3D LIM with a basic GPU based pedestrian model proves it is possible to construct interactive 3D visualisations with dynamic human and vehicular elements. It also highlights the advantages of a GPU based simulation for both computational power and visualisation.

Generating the obstacles from the environmental plan worked satisfactorily, but the manual construction of the road network and pedestrian emitters and exits would significantly hinder the workflow. It would be of interest to examine the automation of the construction of road network and pedestrian emitters and exits from inside the 3D LIM. For example, defining doorway regions may provide a method for creating entrances and exits in the simulation. If this is possible, then one future goal should be to integrate the pedestrian model directly into the 3D LIM prototype, so there will be no need to export the design to a separate system.

Regarding pedestrian journeys, the navigational method using repulsors did provide a direction-finding method, but it may be more useful to combine this method with more complex ways of avoiding the local minima problem. The repulsor method would then work as a low-level avoidance scheme handling traffic and other pedestrians, whilst the agents would utilise a higher-level navigational scheme to control their overall goals. Also, implementing some form of damping on directional change of pedestrians is likely to be necessary.

One potentially useful extension to the system would be to integrate terrain into the simulation. By extending the pedestrian simulation to take account of a grid of height data, terrain integration would be possible in a method similar to that used for the flood model integration.

As for the visual quality of the simulation, each pedestrian and vehicle is currently homogenous, which may lead to a lack of acceptance by the viewer. Galvao et al demonstrate that it is possible to implement different appearances for pedestrians using GPU based techniques [115]. Therefore, it would be of interest to examine the viewer acceptance based on different levels of realism required for pedestrians inside interactive 3D visualisations.

This chapter highlights the possibilities of connecting pedestrian simulations with a 3D LIM. It is essentially preliminary work that could be used for visualisation purposes, but the model is not yet calibrated against real behaviours and, as such, cannot be used for predicting pedestrian behaviour.

Despite this restriction and the current limitations of the traffic simulation, the author believes that integrating pedestrian modelling with a 3D LIM shows substantial promise.

Chapter 9
ON SITE DISSEMINATION OF MODEL DATA

This chapter examines the ability to disseminate the data held in the 3D LIM to on site users. Firstly, it explains the technical implementation needed to allow on site design before considering the application of this technology to location aware mobile phones.

9.1 ON SITE DESIGN

Although the 3D LIM prototype could be used in a variety of settings, it still meant access to the data held in the system required physical access to the computer running the 3D visualisation software. Should a designer want to work on site with the prototype, this would mean that they would have to carry a laptop or similar to site. However, the system could already communicate with a tablet device and, as tablets are capable of connecting to the mobile data networks, a remote linkage to the system via a tablet was conceived. The missing element was the ability to transmit images from the 3D model to the tablet. To overcome this limitation, a rudimentary C++ web server component was added to the plugin system, which is shown in Figure 64. This allowed mobile devices to use the standard HTTP protocol to request a JPEG image from the 3D model. The web server component would receive a URL request with a latitude and longitude as parameters, convert these to model co-ordinates, render the image data for that position using a Simmetry 3d API call and then return that image data to the user. Simultaneous requests could be made to the web server, but the 3D view images were all rendered in the main Simmetry 3d thread in response to user requests whilst threading semaphores were used to co-ordinate the return of image data back to the appropriate user request thread.

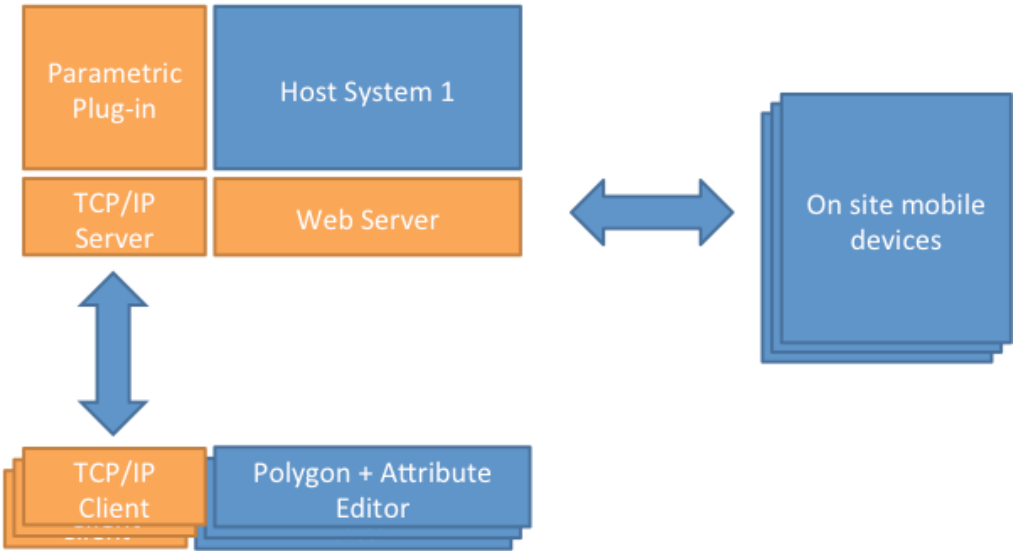


Figure 64 – Web Server component of the plugin architecture

This functionality allowed the tablet interface to receive an image of the 3D model on demand. The tablet interface was extended further to allow connection to multiple models, each running on separate computers, so that the same view from all scenarios could be downloaded to the tablet where the user could move a finger vertically to blend between the images as a method of comparing differences at that viewpoint.

The tablet showed the current position of the device on top of the mapping view. This meant that a user of the 3D LIM could go on to site and use the point and click interface to choose a position and direction in the connected visualisations. Next, they could then acquire the same view in the connected scenarios as they themselves had of the site. An example of this can be seen in Figure 65.

After discussions with the developer of Simmetry 3d, that API was extended to also allow generation of a 360° panorama at a point, which meant the user could also download an interactive panorama to the tablet. The panorama file was requested in the same way as the image request was processed from a user request and the resulting file sent from the web server back to the tablet, so that it could be launched from the editing tablet application into an existing interactive panorama viewer, Walkabout 3d[32]. This was designed to give a more interactive experience with the 3D model than multiple image requests for one point would.

[32] http://www.walkabout3d.com/Mobile/

Figure 65 - Tablet device displaying a planning proposal on site © Sigrid Hehl-Lange

This enabled the designer to compare any view on site with their 3D model, but by using the tablet design interface, they could also edit the parameters of the 2D plan and receive visual feedback from the altered 3D visualisation. If the tablet user interface contained a full editing system for drawing regions then the designer would have full control over the 3D landscape model. This functionality may be very useful for site surveys, or in alteration of designs in response to influences perceived whilst on site.

9.2 CONNECTING WITH SMART PHONES

Mobile phone ownership has increased rapidly in the last decade, but the type of devices being sold is changing. Ofcom data states that adoption of a smartphone (a mobile phone that has a web browser and internet connectivity) increased in the UK population to 27% in October 2011 and the ownership figure rises to 47% for the age range of 12-15 [116]. These devices have a high-resolution colour display, increasingly rapid data connections, Global Positioning Service (GPS) and compass. The GPS and compass combine to allow the smartphone to determine its position and direction.

Therefore, with the general population increasingly using smartphones, one possible method to increase public participation of landscape designs would be to provide access to the visualisations usually associated with public participation via their smartphone. This would continue the trend of providing planning portals for people to access, but rather than access in their home, they would be able to view them when and wherever they wished. In other words, the visualisations would come to the person, rather than the other way round. This would allow the public to reference a 3D landscape model from any position, which would avoid the situation of only providing a handful of chosen 3D views of a proposal. This method of accessing visualisations has the potential to create a more democratic method of access to the design.

It would be possible to provide an interface similar to that implemented on the tablet on the smaller screens of smartphones. However, using the tablet interface would still require the user to understand a site plan, demanding user interaction to ascertain the required viewpoint. Anyone accessing without understanding the site plan, would meet a barrier to using the system. Any attempt to include more people in public participation should aim to reduce the barriers to accessing planning information. Therefore, rather than accessing the visualisations using a site plan, a new interface was constructed that utilised the position and direction information accessible in a standard smartphone web browser.

By combining the web server in the 3D LIM with smartphones that have access to location information available via JavaScript objects, it was then possible to provide a URL that a user types into their phone browser. The corresponding view is then returned to the user as a standard HTML document. This makes the user interface as simple as pointing a phone in a particular direction and loading a web page. An example of how this looks to a user is shown in Figure 66. A new view of the 3D model can be requested by simply refreshing the web page, which will automatically send a new position and direction to the web server.

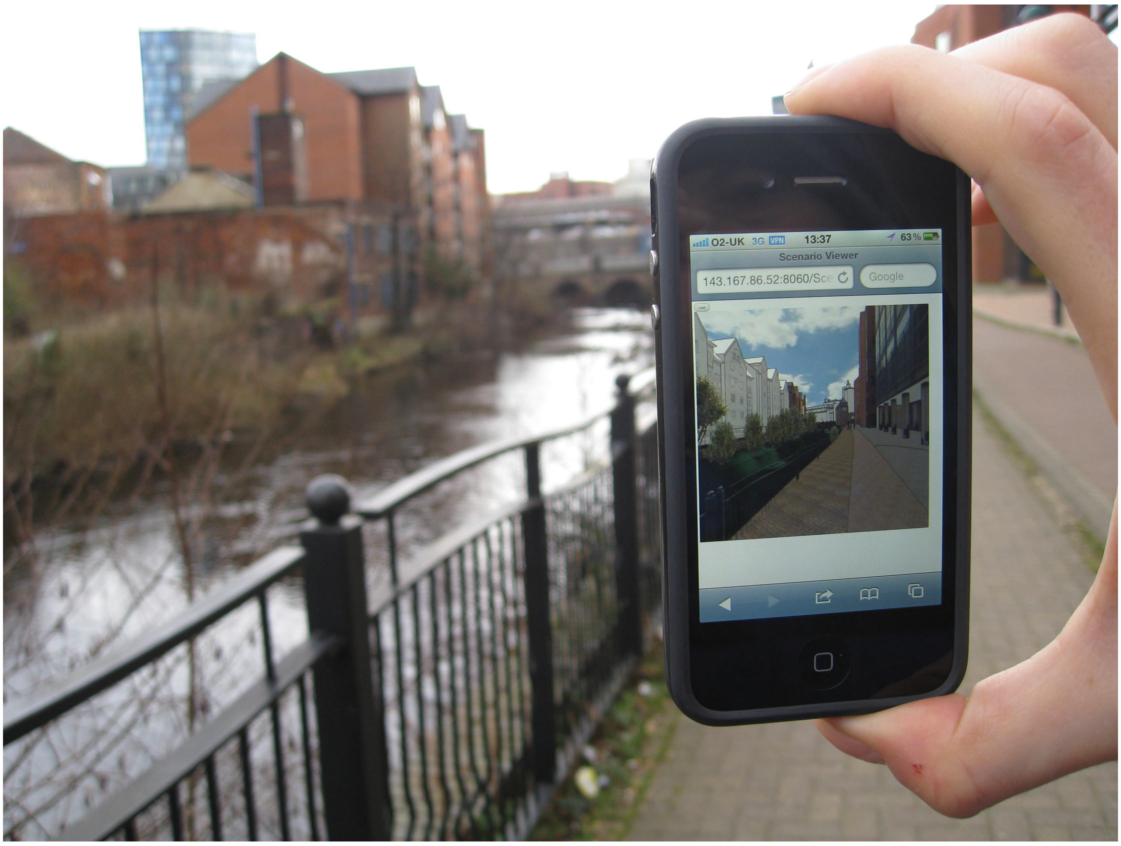


Figure 66 – Smartphone showing a design for the site through a web browser

It was also possible to provide access to two scenarios from one web page, but a master web server had to be configured with the network address to the other scenario web server. The server handling the user request would generate the appropriate view, but it would also request the other scenario server to do the same for the position and direction parameters. Finally, when it had all the appropriate data, it would then return the image data to the mobile device. When the two images were loaded, it was then possible to blend between the two scenario images with a vertical finger gesture as a method of comparing the differences between designs.

9.3 Results

The system was tested with both procedurally generated and manually created models loaded into Simmetry 3d with the 3D LIM plugin running. It proved possible to use the tablet system on site to view and edit a remote 3D landscape model via a 3G data connection. The production and transmission of the 3D views would take more than the previously discussed one-second metric for a system response due to the rendering of the model to an image and the transmission speeds of the mobile data network. The panorama files take even longer to produce as they require multiple views to be rendered and the resultant file size is larger. This system performance cannot therefore be deemed interactive, although it did provide an easy method of viewing the model within the context of the site.

Using the GPS and the compass automatically to both ascertain and transmit location and direction was possible. When it worked successfully, it provided a very easy to use method of accessing a 3D landscape model. Unfortunately, there can be inaccuracy in the detected position, which could mean when standing by the riverside, the server returned a view of the model from one or two metres into the river. Moving position slightly could rectify this, but the erroneous views may prove off-putting to users, especially if they occurred regularly. Nevertheless, with the introduction of higher accuracy GPS systems, such as the European Galileo project [117], the positioning in smartphones may become more precise and overcome this potential issue.

One obvious drawback to this system is that fast mobile data networks do not provide universal coverage, so if a proposal were located in one of these holes, the above system would fail to operate. Designing on site could still be possible if an ad-hoc wireless network were to be set up to a base computer that hosted the model and the user stayed in range, but it may mean this mobile type of interface is more suited to urban sites rather than more rural ones.

The prototype as currently implemented would not provide a scalable solution for high demand scenarios as it relies on the Simmetry 3d API to move the viewer to a particular position and then render that view. However, this could be overcome in the future with a multi-threaded rendering solution.

9.4 DISCUSSION

Given that it is possible to provide public on-site access to 3D visualisations, it seems a sensible strategy to examine this to ascertain whether it does provide benefits over more traditional forms of public consultation. The integration of social networks and online planning portals to the web site interface on the smartphone provides the possibility of allowing users to give their feedback on landscape proposals instantaneously. This could be combined with recording whereabouts in the proposal people request views, much like the presence tracking procedure detailed in Chapter 3. This data would end up being able to produce tracking maps that could be overlaid on the 3D model to give designers and planners an insight into popular, or controversial areas of a design. Smartphones would also present an interesting medium to communicate the results of linked models whether in the 3D view or through more standard visualisation techniques.

The tablet interface should also be extended to allow drawing tools that can edit the polygons in the plan and then it would be interesting to examine if designers would choose to use the 3D LIM on site.

As a final note, although graphics hardware on mobile devices continues to improve, it is likely the geometric complexity of 3D landscape models will continue to remain beyond the capacity of mobile devices to render interactively. Therefore, to further enhance the feedback to the user it may be possible to consider a “cloud” based rendering solution that sends video to the client device rather than geometric data, such as the scheme presented by Lamberti and Sanna [118].

Chapter 10
OVERALL RESULTS, DISCUSSION AND CONCLUSIONS

The final chapter in this thesis draws together the results in the previous chapters, discusses these findings, highlights the future directions that 3D LIM research could be taken in and provides the conclusions on the research performed.

10.1 OVERALL RESULTS

The position of real-time 3D graphics alongside other visualisation media has been explored, whereby it was found that 2D plans and interactive 3D visualisations were highly rated by a set of experts. This could also be observed when analysing video of experts discussing a landscape design proposal. The novel video-based technique also highlighted the potential for differences in observed behaviour and self-reported ranking, which researchers should be aware of.

It has also been shown that it is possible to apply the tracking of the movement of users inside interactive 3D visualisations to urban design. The resultant data can be visualised in the context of 3D models, or aggregated on a set of 2D plans to provide comparative feedback to the designer of potential usage patterns in a range of designs.

Moreover, this thesis has presented a theoretical framework for the definition and usage of 3D LIM for site-based landscape design. It has been shown, through the construction of a prototype, that it is possible to implement the key theoretical features of a 3D LIM. Much research has already been undertaken on automating the construction of landscape models through procedural modelling and the prototype constructs a 3D landscape model using a basic form of this technique. Crucially though, it creates the 3D landscape model in a format that is easily editable by a designer through a 2D plan, linked directly to a 3D visualisation shown alongside that 2D plan. The linked dual views are based on the findings of the media choice experiments. The prototype was extended to work as a server to which remote clients could connect and control both the 2D plan and 3D visualisation, thereby allowing a designer to work away from the host computer with a portable tablet interface.

The procedural generation system was also used to create a semantic 3D landscape model by providing each element in the 3D model with a set of key value pairs denoting attributes that defined non-visual aspects of the design. It was proven that graphic shaders could be created that used these tags to interactively colour and analyse the model.

By extending this tagging system and incorporating the 3D landscape model height data, a range of different analytical models have been integrated into the 3D LIM prototype namely: interactive real-time geo-spatial assessments, a Netica Bayesian Network, an Envi-met microclimate model, and an ISIS flood model. It was also shown that a GPU agent based pedestrian simulation could be integrated using data held in the 2D plan and the generated 3D model of the 3D LIM.

Although the analytical models simulate very different systems, these integrations separated into two groups: online and offline, i.e. those which provide the potential for interactive design and those which do not. Nonetheless, it has been shown that even for the offline analytical modules it is still possible to use the data held in the 3D LIM to reduce the time taken to create input files for linked analytical systems and to visualise the results produced by these back within the 3D landscape model.

The devolved tablet interface for the 3D LIM prototype was extended to allow on-site editing of one or more landscape designs using a mobile internet connection. This on-site technology was reused to disseminate the data held in the 3D LIM prototype via a web browser interface that uses the integral GPS and compass of a smartphone to download the relevant view of one or more landscape scenarios. Given the increasing adoption of smartphones by the public, this style of interface may provide a method for increasing public participation in landscape planning.

Finally, although the 3D LIM employed procedural generation to automate the process of landscape model construction, it proved possible to use some of the techniques described herein on manually constructed models. So, should a model of an area already exist, it would be possible to integrate the model height data to flood simulations (although not the Manning export) and provide geo-referenced visualisations to the web browsers of smartphones.

10.2 Discussion

This thesis has focused on establishing a framework for, and creating, a prototype to prove that it is possible to implement the key features of a 3D LIM, but this is really just the beginning. The prototype was created to be functional, but there is still work to be done to make it user friendly enough for a landscape professional to use it unaided. Also, the prototype suffers from a series of limitations that need addressing, as discussed at the end of Chapter 5, especially that of the lack of highly controllable terrain modification, more complex procedural generation and texture mapping. Once this has been resolved, the next step should be to use the prototype to test the theoretical positioning of a 3D LIM within the different stages of the landscape design process and then establish how the 3D LIM could be used within participatory landscape planning processes.

Furthermore, in addition to testing the usability of the user interfaces, further study could be made into the linking of more analyses to the system, such as ecological measures to predict bio-diversity performance. It is hoped that extensions to the procedural tagging system would continue to provide a route for integration of additional analytical models. Equally, it would be of interest to create interoperability between 3D LIM analyses and therefore create integrated modelling. For example, connecting the pedestrian movement model with a flooding simulation should offer greater insight to the designer than simply running the two models side by side.

One of the most prominent issues likely to limit adoption of 3D LIMs will almost certainly be the difficulty of gathering sufficient data to drive them. Currently, 2D GIS data has become prevalent in local authorities and planning organisations, and 3D city models are becoming more widely available built from photogrammetric sources, such as the ZMapping[33] commercial service, or crowd sourced

[33] http://www.zmapping.com/urban3dmodelling.htm

methods, such as Google Building Maker[34]. These efforts tend to focus on urban form and either produce single elements or an entire 3D model, both of which hard to edit in response to landscape alterations, or to connect to a 3D LIM. Instead of simply focusing on constructing geometric 3D models, perhaps a better approach would be to consider the whole of the surface of the Earth as one overall containing region, which may be progressively subdivided into smaller and smaller regions. Each region would then have a set of key and value attributes. This format, when combined with terrain data, would allow procedural generation techniques to build 3D form, and 3D LIMs to analyse them. This scheme would also work with manual modelling of 3D elements for regions as long as the manually constructed models correlated exactly with the boundaries of each subdivision and tagged correctly. OpenStreetMap[35] is a planet wide database of crowd sourced map data using traditional 2D GIS techniques to map the world as points, lines and polygons and employs a free tag system to allow map editors to associate a set of key and value attributes against these GIS primitives. Applying the attributed region approach to the crowd sourced OpenStreetMap data collection system would provide a rich, up to date database of the surface of the planet. This would satisfy the data requirements of 3D LIMs and other procedural generation systems and overcome the landscape modelling data collation problem.

Looking forward, it would also be interesting to use the 3D LIM to simulate temporal effects on the design. This would probably involve simulations in various time periods: diurnal (day/night), annual (seasonal weather) and longer-term cycles (wear and tear/vegetation growth).

As one final thought, perhaps in the future it will be possible to go beyond the simple provision of tools to support the landscape architect and allow the computer itself to become a member of the design team. Certainly, it is possible to automate the construction and analysis of landscape designs; so where the computer could produce multiple designs and pick the elements that perform better than others, it would give rise to a form of evolutionary landscape design for creating the sustainable landscapes of the future.

[34] http://sketchup.google.com/3dwarehouse/buildingmaker

[35] http://www.openstreetmap.org

10.3 CONCLUSIONS

It can be concluded that by adding parametric data to a digital 3D landscape model, it can be used for more than just visualisation purposes. It can also be used to aid understanding of landscape performance by exporting the information held in the 3D geometric model to drive different styles of analytical models. Non-spatial results of these simulations can be visualised alongside the 3D model and spatial results of linked analyses can be visualised within the context of the 3D model. To this end, graphic shaders provide a method for interactively displaying predicted landscape performance data overlaid on to the 3D model. Procedural modelling can be used to generate 3D form, but it is also possible to use this generation stage to automate the calculation of the parameters to be held against 3D elements that in turn will drive the linked analyses.

By creating a system that combines all these methods and an editing system that stores multiple designs, it is also feasible to provide differential analysis based on a chosen reference design, such as the status quo. Again, graphic shaders provide a method for visualising differences in results spatially.

Finally, by extending the 3D model and rendering system into a client/server architecture, it is possible to allow remote clients to control and edit stored landscape designs, even on-site. Thus, considering the definition of a 3D LIM (*defined as an interactive software tool that supports the landscape design process in both the construction and judgment of a landscape design via 3D landscape models*), it can be concluded that the creation of a 3D LIM is certainly practicable.

Appendix A

MEDIA CHOICE EXPERIMENT 1 QUESTIONNAIRE

This is a version of the questionnaire used in the sustainability experiment (reduced in size to fit, original sized to A4)

VISUALISATION MEDIA TYPES QUESTIONNAIRE

1. Please **tick** how often, in your previous experience, you have seen each media type used to communicate planning proposals:

	Always	Usually	Occasionally	Seldom	Never
2D map	☐	☐	☐	☐	☐
Photomontage	☐	☐	☐	☐	☐
Walk-through video	☐	☐	☐	☐	☐
3D interactive visualisation	☐	☐	☐	☐	☐

2. For each of the following media, please **tick** the suitability for aiding your understanding of the scenarios:

	Bad			Average			Good
2D map	☐	☐	☐	☐	☐	☐	☐
Photomontage	☐	☐	☐	☐	☐	☐	☐
Walk-through video	☐	☐	☐	☐	☐	☐	☐
3D interactive visualisation	☐	☐	☐	☐	☐	☐	☐

3. For each of the following media types, please **tick** rating the extra information imparted compared to just using the maps provided?

	Less clear			No change			More clear
Photomontage	☐	☐	☐	☐	☐	☐	☐
Walk-through video	☐	☐	☐	☐	☐	☐	☐
3D interactive visualisation	☐	☐	☐	☐	☐	☐	☐

4. Considering the visual quality of the 3D visualisations, do you prefer the full-screen "video game" style interface or the "Windows and menus" style?

Prefer full-screen video game style ☐	No difference between types ☐	Prefer Windows and menus style ☐

5. Do you have additional comments on media types used?

Continue comments overleaf

Appendix B

MEDIA CHOICE EXPERIMENT 2 QUESTIONNAIRE

This is a version of the questionnaire used in the media choice experiment (reduced in size to fit, original sized to A4)

URSULA

SWSG 2nd WORKSHOP ON URBAN RIVER CORRIDORS
VISUALISATION QUESTIONNAIRE - SESSION 3

PART A

1. Please **tick** how often, in your previous experience, you have seen each media type used to communicate planning proposals:

	Always	Usually	Occasionally	Seldom	Never
Paper plan					
Physical model					
Printed 3D perspectives					
3D visualisation (e.g. Sketchup)					
3D walkthrough with game controller					
3D walkthrough with game controller and glasses					

2. Please **rank (using each number only once)** the following media in order of suitability for aiding your understanding of this Nursery Street proposal (1 – most suitable, 6 – least suitable):

Paper plan	
Physical Model	
Printed 3D perspectives	
3D visualisation (Sketchup)	
3D walkthrough with game controller	
3D walkthrough with game controller and glasses	

3. Please **rank (using each number only once)** the following media in order of suitability for aiding your discussions with other participants of this workshop (1 – most suitable, 6 – least suitable):

Paper plan	
Physical Model	
Printed 3D perspectives	
3D visualisation (Sketchup)	
3D walkthrough with game controller	

Appendix C

CONTROLLER QUESTIONNAIRE

This is a version of the questionnaire used in the 3D visualisation controller survey (reduced in size to fit, original sized to A4)

The University Of Sheffield.

CONTROLLER WORKSHOP QUESTIONNAIRE

1. Which interactive 3D model control method did you prefer?

Point and click ☐	Walk-through ☐	No preference ☐

2. Can you explain your preference?

Continue comments overleaf

3. *For improving your understanding of the models*, please **tick** once for each category rating how useful each one was?

	Least useful		Average		Most useful
Point and click	☐	☐	☐	☐	☐
Walk-through	☐	☐	☐	☐	☐

4. *As an aid to discussion of the models*, please **tick** once for each category rating how useful each one was?

	Least useful		Average		Most useful
Point and click	☐	☐	☐	☐	☐
Walk-through	☐	☐	☐	☐	☐

5. Do you have additional comments on the software tools used?

Continue comments overleaf

Appendix D

COMPANION DVD

This appendix contains a concise description of the contents of the companion DVD.

Folder	Description
Videos	A collection of videos showing: • designing using the 3D LIM • UHI modelling results overlaid on the a 3D LIM • On site comparison of multiple designs using a tablet • Tablet control of the 3D LIM • Demonstration of pedestrian and car agent interaction
PDF	An electronic version of this document
Source	The Code folder contains example source code for a 3D LIM plugin. The code is for reference purposes to aid future researchers developing 3D LIMs and does not include Simmetry or Sketchup integration. Brief documentation is provided in Documentation/html/index.html The Shader folder contains the source of the OpenGLSL code used in the 3D LIM prototype.

REFERENCES

[1] P. Paar, “Landscape visualizations: Applications and requirements of 3D visualization software for environmental planning,” *Computers, Environment and Urban Systems*, vol. 30, no. 6, pp. 815–839, Nov. 2006.

[2] M. Déjeant-Pons, “The European Landscape Convention,” *Landscape Research*, vol. 31, no. 4, pp. 363–384, Oct. 2006.

[3] C. Eastman, “General purpose building description systems,” *Computer-Aided Design*, vol. 8, no. 1, pp. 17–26, 1976.

[4] T. Asawa, A. Hoyano, and K. Nakaohkubo, “Thermal design tool for outdoor spaces based on heat balance simulation using a 3D-CAD system,” *Building and Environment*, vol. 43, no. 12, pp. 2112–2123, Dec. 2008.

[5] E. Morgan, L. Gill, E. Lange, and D. Romano, “Rapid Prototyping of Urban River Corridors Using 3D Interactive, Real-time Graphics,” in *Proceedings Digital Landscape Architecture 2009*, Anhalt University of Applied Sciences, Malta, 2009, pp. 198–205.

[6] S. Kidd, “Landscape planning: reflections on the past, directions for the future,” in *The Routledge Companion to Landscape Studies*, P. Howard, I. Thompson, and E. Waterton, Eds. Routledge, Oxon, UK, 2013, pp. 366–382.

[7] M. Carroll, *Earthly paradises : ancient gardens in history and archaeology*. London : British Museum Press, 2003.

[8] M. L. Gothein, *A history of garden art*, vol. 1. New York : Hacker Art Books, 1966.

[9] R. E. Ehrenberg, *Mapping the World: An Illustrated History of Cartography*. National Geographic Books, 2005.

[10] H. Repton and E. Malins, *The red books of Humphry Repton*. London: Basilisk Press, 1976.

[11] E. Lange, “Vista management in Acadia National Park,” *Landscape and Urban Planning*, vol. 19, no. 4, pp. 353–376, 1990.

[12] E. Lange, “Integration of computerized visual simulation and visual assessment in environmental planning,” *Landscape and Urban Planning*, vol. 30, no. 1–2, pp. 99–112, Oct. 1994.

[13] E. R. Tufte, *Visual Explanations: Images and Quantities, Evidence and Narrative*. Graphics Press, 1997.

[14] A. Herwig and P. Paar, “Game engines: tools for landscape visualization and planning,” in *Trends in GIS and Virtualization in Environmental Planning and Design*, E. Buhmann, U. Nothelfer, and M. Pietsch, Eds. Heidelberg: Wichmann, 2002, pp. 161–172.

[15] S. M. Ervin, “Digital landscape modeling and visualization: a research agenda,” *Landscape and Urban Planning*, vol. 54, no. 1–4, pp. 49–62, May 2001.

[16] W. Ribarsky, T. Wasilewski, and N. Faust, “From Urban Terrain Models to Visible Cities,” *IEEE Comput. Graph. Appl.*, vol. 22, no. 4, pp. 10–15, Jul. 2002.

[17] E. Lange, “The limits of realism: perceptions of virtual landscapes,” *Landscape and Urban Planning*, vol. 54, no. 1–4, pp. 163–182, May 2001.

[18] K. Boulanger, S. Pattanaik, and K. Bouatouch, “Rendering grass terrains in real-time with dynamic lighting,” in *ACM SIGGRAPH 2006 Sketches*, Boston, Massachusetts, 2006.

[19] H. Baumann, “Hayelberga - Integrated real-time modelling and visualisation,” in *Trends in Real-Time Landscape Visualisation and Participation Proceedings at Anhalt University of Applied Sciences 2005*, 2005, pp. 303–306.

[20] P. Mueller, P. Wonka, S. Haegler, A. Ulmer, and L. Van Gool, “Procedural modeling of buildings,” *ACM Trans. Graph.*, vol. 25, no. 3, pp. 614–623, Jul. 2006.

[21] R. Hoinkes and E. Lange, “3D for free. Toolkit expands visual dimensions in GIS,” *GIS World*, vol. 8, no. 7, pp. 54–56, 1995.

[22] P. Wonka, M. Wimmer, F. Sillion, and W. Ribarsky, “Instant architecture,” in *International Conference on Computer Graphics and Interactive Techniques*, 2003, pp. 669–677.

[23] L. Perrin, N. Beauvais, and M. Puppo, “Procedural landscape modeling with geographic information: the IMAGIS approach,” *Landscape and Urban Planning*, vol. 54, no. 1–4, pp. 33–47, May 2001.

[24] K. Lynch and G. Hack, *Site planning*, 3rd ed. Cambridge, Massachusetts, USA: The MIT Press, 1984.

[25] I. D. Bishop, "Visualization for participation: the advantages of realtime," in *Trends in Real-Time Landscape Visualisation and Participation Proceedings at Anhalt University of Applied Sciences 2005*, E. Buhmann, P. Paar, I. D. Bishop, and E. Lange, Eds. Berlin: Wichmann, 2005, pp. 2–15.

[26] C. Steinitz, "A framework for theory applicable to the education of landscape architects (and other environmental design professionals)," *Landscape Journal*, vol. 9, no. 2, pp. 136–143, 1990.

[27] M. S. Kibria, S. Zlatanova, L. Itard, and M. Dorst, "GeoVEs as Tools to Communicate in Urban Projects: Requirements for Functionality and Visualization," in *3D Geo-Information Sciences*, J. Lee and S. Zlatanova, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2009, pp. 379–395.

[28] H. Buchholz, J. Döllner, L. Ross, and B. Kleinschmit, "Automated Construction of Urban Terrain Models," in *Progress in Spatial Data Handling, 12th International Symposium on Spatial Data Handling, Springer*, 2006, pp. 547–562.

[29] E. Lange and S. Hehl-Lange, "Citizen participation in the conservation and use of rural landscapes in Britain: the Alport Valley case study," *Landscape and Ecological Engineering*, vol. 7, no. 2, pp. 223–230, 2011.

[30] O. Schroth, "From Information to Participation - Interactive Landscape Visualization as a Tool for Collaborative Planning," Dissertation No. 17409, ETH Zürich, 2007.

[31] S. Zlatanova, M. Dorst, and L. Itard, "The role of visual information in design tools for urban renewal," in *W21*, Rotterdam, Netherlands, 2007.

[32] L. Coconu, O. Deussen, and H.-C. Hege, "Real-time pen-and-ink illustration of landscapes," in *Proceedings of the 4th international symposium on Non-photorealistic animation and rendering*, Annecy, France, 2006, pp. 27–35.

[33] P.-L. Lesage and M. Visvalingam, "Towards sketch-based exploration of terrain," *Computers & Graphics*, vol. 26, no. 2, pp. 309–328, Apr. 2002.

[34] M. Nienhaus, "Real-Time Non-Photorealistic Rendering Techniques for Illustrating 3D Scenes and their Dynamics," University of Potsdam, 2005.

[35] S. Hehl-Lange, "Structural elements of the visual landscape and their ecological functions," *Landscape and Urban Planning*, vol. 54, no. 1–4, pp. 107–115, May 2001.

[36] J. Isaacs, R. Falconer, and D. Blackwood, "A Unique Approach to Visualising Sustainability in the Built Environment," in *Proceedings of the 2008 International Conference Visualisation*, 2008, pp. 3–10.

[37] E. Morgan, L. Gill, E. Lange, and M. Dallimer, "Integrating bird survey data into real-time 3D visual and aural simulations," in *Digital Landscape Architecture 2012*, Berlin, pp. 492–8.

[38] J. Nichol and M. S. Wong, "Modeling urban environmental quality in a tropical city," *Landscape and Urban Planning*, vol. 73, no. 1, pp. 49–58, Aug. 2005.

[39] C. W. Reynolds, "Flocks, herds and schools: A distributed behavioral model," in *Proceedings of the 14th annual conference on Computer graphics and interactive techniques*, New York, NY, USA, 1987, pp. 25–34.

[40] D. Helbing, P. Molnar, and F. Schweitzer, "Self-Organization Phenomena in Pedestrian Crowds," in *Individual to Collective Dynamics*, Gordon and Breach, 1997, pp. 569–577.

[41] D. Cavens, C. Gloor, J. Illenberger, E. Lange, K. Nagel, and W. A. Schmid, "Distributed intelligence in pedestrian simulations," in *Pedestrian and Evacuation Dynamics 2005*, N. Waldau, P. Gattermann, H. Knoflacher, and M. Schreckenberg, Eds. Springer Berlin Heidelberg, 2007, pp. 201–212.

[42] M. Batty, "Defining geodesign (= GIS + design ?)," *Environment and Planning B: Planning and Design*, vol. 40, no. 1, pp. 1–2, 2013.

[43] S. Ervin, "Landscape Meta-Modeling," in *Trends in Knowledge-Based Landscape Modeling*, Dessau, 2006, pp. 2–15.

[44] R. G. Laycock and A. M. Day, "Rapid generation of urban models," *Computers & Graphics*, vol. 27, no. 3, pp. 423–433, Jun. 2003.

[45] I. D. Bishop, C. Stock, and K. J. Williams, "Using virtual environments and agent models in multi-criteria decision-making," *Land Use Policy*, vol. 26, no. 1, pp. 87–94, Jan. 2009.

[46] B. Piper, C. Ratti, and H. Ishii, "Illuminating clay: a 3-D tangible interface for landscape analysis," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, New York, NY, USA, 2002, pp. 355–362.

[47] I. Rakkolainen and T. Vainio, "A 3D City Info for mobile users," *Computers & Graphics*, vol. 25, no. 4, pp. 619–625, Aug. 2001.

[48] J. Evans-Cowley, "There's an App for That," *International Journal of E-Planning Research*, vol. 1, no. 2, pp. 79–87, 32 2012.

[49] E. Lange, "99 volumes later: We can visualise. Now what?," *Landscape and Urban Planning*, vol. 100, no. 4, pp. 403–406, Apr. 2011.

[50] E. R. Tufte, *Envisioning Information*. Cheshire, CT: Graphics Press, 1990.

[51] R. E. Klosterman, "Planning Support Systems: A New Perspective on Computer-Aided Planning," *Journal of Planning Education and Research*, vol. 17, no. 1, pp. 45–54, Sep. 1997.

[52] S. R. J. Sheppard, "Landscape visualisation and climate change: the potential for influencing perceptions and behaviour," *Environmental Science & Policy*, vol. 8, no. 6, pp. 637–654, Dec. 2005.

[53] Appleton K. and Lovett A., "GIS-based visualisation of rural landscapes: defining 'sufficient' realism for environmental decision-making," *Landscape and Urban Planning*, vol. 65, pp. 117–131, Oct. 2003.

[54] B. Orland, K. Budthimedhee, and J. Uusitalo, "Considering virtual worlds as representations of landscape realities and as tools for landscape planning," *Landscape and Urban Planning*, vol. 54, no. 1–4, pp. 139–148, May 2001.

[55] K. Al-Kodmany, "Using visualization techniques for enhancing public participation in planning and design: process, implementation, and evaluation," *Landscape and Urban Planning*, vol. 45, no. 1, pp. 37–45, Sep. 1999.

[56] J. L. Lewis and S. R. J. Sheppard, "Culture and communication: Can landscape visualization improve forest management consultation with indigenous communities?," *Landscape and Urban Planning*, vol. 77, no. 3, pp. 291–313, Aug. 2006.

[57] N. R. Feimer, "Environmental perception: The effects of media, evaluative context, and observer sample," *Journal of Environmental Psychology*, vol. 4, no. 1, pp. 61–80, Mar. 1984.

[58] N. Bates-Brkljac, "Assessing perceived credibility of traditional and computer generated architectural representations," *Design Studies*, vol. 30, no. 4, pp. 415–437, Jul. 2009.

[59] K. Al-Kodmany, "Visualization tools and methods in community planning: From freehand sketches to virtual reality," *J. Plan. Lit.*, vol. 17, no. 2, pp. 189–211, Nov. 2002.

[60] E. Lange and S. Hehl-Lange, “Combining a participatory planning approach with a virtual landscape model for the siting of wind turbines,” *Journal of Environmental Planning and Management*, vol. 48, no. 6, pp. 833–852, 2005.

[61] E. Lange and S. Hehl-Lange, “Making visions visible for long-term landscape management,” *Futures*, vol. 42, no. 7, pp. 693–699, 2010.

[62] S. Burch, S. R. J. Sheppard, A. Shaw, and D. Flanders, “Planning for climate change in a flood-prone community: municipal barriers to policy action and the use of visualizations as decision-support tools,” *Journal of Flood Risk Management*, vol. 3, no. 2, pp. 126–139, Mar. 2010.

[63] A. Werner, O. Deussen, J. Dollner, H.-C. Hege, P. Paar, and J. Rekittke, “Lenné3D – Walking through Landscape Plans,” in *Trends in Real-time Visualization and Participation*, Anhalt, 2005, pp. 48–59.

[64] O. Schroth, U. W. Hayek, E. Lange, S. R. J. Sheppard, and W. A. Schmid, “Multiple-Case Study of Landscape Visualizations as a Tool in Transdisciplinary Planning Workshops,” *Landscape Jrnl.*, vol. 30, no. 1, pp. 53–71, Jan. 2011.

[65] I. D. Bishop, J. R. Wherrett, and D. R. Miller, “Assessment of path choices on a country walk using a virtual environment,” *Landscape and Urban Planning*, vol. 52, no. 4, pp. 225–237, 2001.

[66] K. Appleton and A. Lovett, “Display Methods for Real-Time Landscape Models–An Initial Comparison,” in *Trends in Real-Time Landscape Visualisation and Participation, Wichmann, Heidelberg*, 2005, pp. 246–253.

[67] J. D. Salter, C. Campbell, M. Journeay, and S. R. J. Sheppard, “The digital workshop: Exploring the use of interactive and immersive visualisation tools in participatory planning,” *Journal of Environmental Management*, vol. 90, no. 6, pp. 2090–2101, May 2009.

[68] V. Kumar, J. R. Rouquette, and D. N. Lerner, “Integrated modelling for Sustainability Appraisal for Urban River Corridor (re)-development,” *Procedia Environmental Sciences*, vol. 13, pp. 687–697, 2012.

[69] L Pattacini, S Moore, M Burton, B. Davison, L. Gill, A. Hathway, J. Henneberry, S Hornby, V Kumar, E Morgan, P Nunns, J Rouquette, E Shaw, V Stovin, P Warren, L Wu, and D Lerner, *Ursula Information Pack - Wicker Riverside: Sustainable development options considered by URSULA - URSULA working paper no 9*. .

[70] A. Drachen and A. Canossa, “Analyzing spatial user behavior in computer games using geographic information systems,” in *Proceedings of the 13th International MindTrek Conference: Everyday Life in the Ubiquitous Era*, New York, NY, USA, 2009, pp. 182–189.

[71] L. Chittaro, R. Ranon, and L. Ieronutti, “VU-Flow: A Visualization Tool for Analyzing Navigation in Virtual Environments,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 12, no. 6, pp. 1475 –1485, Dec. 2006.

[72] R. Likert, “A technique for the measurement of Attitudes,” *Archives of Psychology*, vol. 140, pp. 1–55, 1932.

[73] B. Zehner, “Interactive Wind Park Planning in a Visualization Center - Giving Control to the User,” in *Proceedings Digital Landscape Architecture 2009*, Anhalt University of Applied Sciences, Malta, 2009, pp. 16–23.

[74] W. W. Royce, “Managing the development of large software systems: concepts and techniques,” in *Proceedings of the 9th international conference on Software Engineering*, Los Alamitos, CA, USA, 1987, pp. 328–338.

[75] J. Highsmith and A. Cockburn, “Agile software development: the business of innovation,” *Computer*, vol. 34, no. 9, pp. 120 –127, Sep. 2001.

[76] R. B. Miller, “Response time in man-computer conversational transactions,” in *Proceedings of the December 9-11, 1968, fall joint computer conference, part I*, San Francisco, California, 1968, pp. 267–277.

[77] T. Goodman and R. Spence, “The effect of System Response Time on interactive computer aided problem solving,” *SIGGRAPH Comput. Graph.*, vol. 12, no. 3, pp. 100–104, Aug. 1978.

[78] U. Wissen, O. Schroth, E. Lange, and W. A. Schmid, “Approaches to integrating indicators into 3D landscape visualisations and their benefits for participative planning situations,” *Journal of Environmental Management*, vol. 89, no. 3, pp. 184–196, 2008.

[79] S. M. Ervin, “A System for Geodesign,” in *Proceedings of Digital Landscape Architecture 2011*, Anhalt University of Applied Sciences, Dessau, Germany, pp. 145–154.

[80] M. Batty, P. Steadman, and Y. Fukuchi, “Visualization in Spatial Modeling,” in *Complex Artificial Environments: Simulation, Cognition and VR in the Study and Planning of Cities*, J. Portugali, Ed. Springer, 2006, pp. 49–69.

[81] O. Deussen, P. Hanrahan, B. Lintermann, R. Měch, M. Pharr, and P. Prusinkiewicz, "Realistic modeling and rendering of plant ecosystems," in *Proceedings of the 25th annual conference on Computer graphics and interactive techniques*, Orlando, 1998, pp. 275–286.

[82] L. Paul Chew, "Constrained delaunay triangulations," *Algorithmica*, vol. 4, no. 1, pp. 97–108, Jun. 1989.

[83] J. Henneberry, E. Lange, E. Morgan, S. Moore, and N. Zhao, "Physical-Financial Modelling as an Aid to Developers' Decision-making," in *Urban Design in the Real Estate Development Process - Policy Tools and Property Decisions*, S. Tiesdell and D. Adams, Eds. Wiley-Blackwell, 2011, pp. 219–235.

[84] R. G. Laycock and A. M. Day, "Automatically generating roof models from building footprints," in *Proceedings of WSCG*, 2003.

[85] R. G. Laycock, G. D. G. Ryder, and A. M. Day, "Automatic generation, texturing and population of a reflective real-time urban environment," *Computers & Graphics*, vol. 31, no. 4, pp. 625–635, Aug. 2007.

[86] P. Richmond and D. Romano, "Automatic Generation of Residential Areas using Geo-Demographics," in *Advances in 3D Geoinformation Systems*, P. Oosterom, S. van Zlatanova, F. Penninga, and E. Fendel, Eds. Springer, 2008, p. 401.

[87] J. Danahy, "Visualization Data Needs in Urban Environmental Planning and Design," in *Photogrammetric Week "99,"* D. Fritsch and R. Spiller, Eds. Wichmann, Stuttgart, pp. 351–365.

[88] K. Lynch, *The Image of the City*. The MIT Press, 1960.

[89] V. Kumar, A. Holzkaemper, and D. Lerner, "Integrated Meta-Modelling for Decision Support in Integrated Catchment Management," in *Proceedings of iEMSs 2010*, Ottawa, Canada, 2010, pp. 1105–1112.

[90] M. Duespohl, S. Frank, and P. Doell, "A Review of Bayesian Networks as a Participatory Modeling Approach in Support of Sustainable Environmental Management," *Journal of Sustainable Development*, vol. 5, no. 12, p. p1, Nov. 2012.

[91] A. Castelletti and R. Soncini-Sessa, "Bayesian Networks and participatory modelling in water resource management," *Environmental Modelling & Software*, vol. 22, no. 8, pp. 1075–1088, Aug. 2007.

[92] I. Borowski and M. Hare, “Exploring the Gap Between Water Managers and Researchers: Difficulties of Model-Based Tools to Support Practical Water Management,” *Water Resour Manage*, vol. 21, no. 7, pp. 1049–1074, Jul. 2007.

[93] E. Shaw, V. Kumar, D. Lerner, and E. Lange, “Bayesian Belief Networks and Social Objectives: A Canoeing Case Study,” in *Proceedings of iEMSs 2010*, Ottawa, Canada, 2010, pp. 1439–1446.

[94] S. E. Gill, J. F. Handley, A. R. Ennos, and S. Pauleit, “Adapting Cities for Climate Change: The Role of the Green Infrastructure,” *Built Environment*, vol. 33, no. 1, pp. 115–133, 2007.

[95] L. Gill, E. Lange, E. Morgan, and D. Romano, “An analysis of usage of different types of visualisation media within a collaborative planning workshop environment,” *Environment and Planning B: Planning and Design*, vol. 40, no. 4, pp. 742 – 754, 2013.

[96] W. Chow and A. J. Brazel, “Assessing xeriscaping as a sustainable heat island mitigation approach for a desert city,” *Building and Environment*, vol. 47, no. 0, pp. 170–181, Jan. 2012.

[97] Z. W. Kundzewicz, L. J. Mata, N. W. Arnell, P. Döll, P. Kabat, B. Jiménez, T. Oki, Z. çen, and I A Shiklomanov, “Freshwater resources and their management. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,” M L Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson, Eds. Cambridge University Press, Cambridge, UK, 2007, pp. 173–210.

[98] E. Shaw, T. Wild, and D. N. Lerner, *ISIS 2D FLOOD MODELLING OF WICKER RIVERSIDE - Project report no 8*. University of Sheffield, 2011.

[99] Yu, Dapeng, “Diffusion-based modelling of flood inundation over complex floodplains.,” University of Leeds, 2005.

[100] CSIRO, *Floodplain management in Australia. Best Practice Principles and Guidelines*. CSIRO Publishing, Collingwood, Australia, 2000.

[101] J. M. Lameiras, L. Marques, and I. Jørgensen, “Digital Terrain Modelling in Landscape Architecture,” in *Proceedings Digital Landscape Architecture 2009*, Anhalt University of Applied Sciences, Malta, 2009, pp. 63–72.

[102] G. Gröger and L. Plümer, “CityGML – Interoperable semantic 3D city models,” *ISPRS Journal of Photogrammetry and Remote Sensing*, vol. 71, no. 0, pp. 12–33, Jul. 2012.

[103] R. V. Moore and C. I. Tindall, "An overview of the open modelling interface and environment (the OpenMI)," *Environmental Science & Policy*, vol. 8, no. 3, pp. 279–286, Jun. 2005.

[104] K. Joh, M. T. Nguyen, and M. G. Boarnet, "Can Built and Social Environmental Factors Encourage Walking among Individuals with Negative Walking Attitudes?," *Journal of Planning Education and Research*, vol. 32, no. 2, pp. 219–236, Jun. 2012.

[105] E. Papadimitriou, G. Yannis, and J. Golias, "A critical assessment of pedestrian behaviour models," *Transportation Research Part F: Traffic Psychology and Behaviour*, vol. 12, no. 3, pp. 242–255, May 2009.

[106] P. G. Gipps and B. Marksjö, "A micro-simulation model for pedestrian flows," *Mathematics and Computers in Simulation*, vol. 27, no. 2–3, pp. 95–105, Apr. 1985.

[107] J. Dijkstra, H. J. P. Timmermans, and A. J. Jessurun, *A multi-agent cellular automata system for visualising simulated pedestrian activity*. Godalming: Springer-Verlag London Ltd, 2001.

[108] M. Haciomeroglu, R. G. Laycock, and A. M. Day, "Automatic spatial analysis and pedestrian flow control for real-time crowd simulation in an urban environment," *Vis. Comput.*, vol. 24, no. 10, pp. 889–899, Sep. 2008.

[109] P. Richmond, D. Walker, S. Coakley, and D. Romano, "High Performance Cellular Level Agent-Based Simulation with FLAME for the GPU," *Brief Bioinform*, vol. 11, no. 3, pp. 334–347, May 2010.

[110] T. Karmakharm, P. Richmond, and D. Romano, "Agent-based Large Scale Simulation of Pedestrians With Adaptive Realistic Navigation Vector Fields," in *Proceedings of EG UK Theory and Practice of Computer Graphics 2010*, Sheffield, UK, 2010, pp. 67–74.

[111] M. M. Ishaque and R. B. Noland, "Behavioural Issues in Pedestrian Speed Choice and Street Crossing Behaviour: A Review," *Transport Reviews*, vol. 28, no. 1, pp. 61–85, 2008.

[112] A. Willis, N. Gjersoe, C. Havard, J. Kerridge, and R. Kukla, "Human movement behaviour in urban spaces: implications for the design and modelling of effective pedestrian environments," *Environ. Plan. B-Plan. Des.*, vol. 31, no. 6, pp. 805–828, Nov. 2004.

[113] P. G. Gipps, "A behavioural car-following model for computer simulation," *Transportation Research Part B: Methodological*, vol. 15, no. 2, pp. 105–111, Apr. 1981.

[114] C. Gloor, P. Stucki, and K. Nagel, “Hybrid Techniques for Pedestrian Simulations,” in *Cellular Automata*, P. M. A. Sloot, B. Chopard, and A. G. Hoekstra, Eds. Springer Berlin Heidelberg, 2004, pp. 581–590.

[115] R. Galvao, R. G. Laycock, and A. M. Day, “GPU techniques for creating visually diverse crowds in real-time,” in *Proceedings of the 2008 ACM symposium on Virtual reality software and technology*, New York, NY, USA, 2008, pp. 79–86.

[116] OFCOM, “Communications Market Report: UK,” Aug. 2011.

[117] S. Ji, W. Chen, X. Ding, Y. Chen, C. Zhao, and C. Hu, “Potential Benefits of GPS/GLONASS/GALILEO Integration in an Urban Canyon – Hong Kong,” *The Journal of Navigation*, vol. 63, no. 04, pp. 681–693, 2010.

[118] F. Lamberti and A. Sanna, “A Streaming-Based Solution for Remote Visualization of 3D Graphics on Mobile Devices,” *IEEE Transactions on Visualization and Computer Graphics*, vol. 13, no. 2, pp. 247 –260, Apr. 2007.