Sustainability assessment and visualisation in urban environments

A Thesis submitted in partial fulfilment of the requirements of the University of Abertay Dundee for the degree of Doctor of Philosophy

By

John Patrick Isaacs

University of Abertay Dundee

School of Contemporary Sciences

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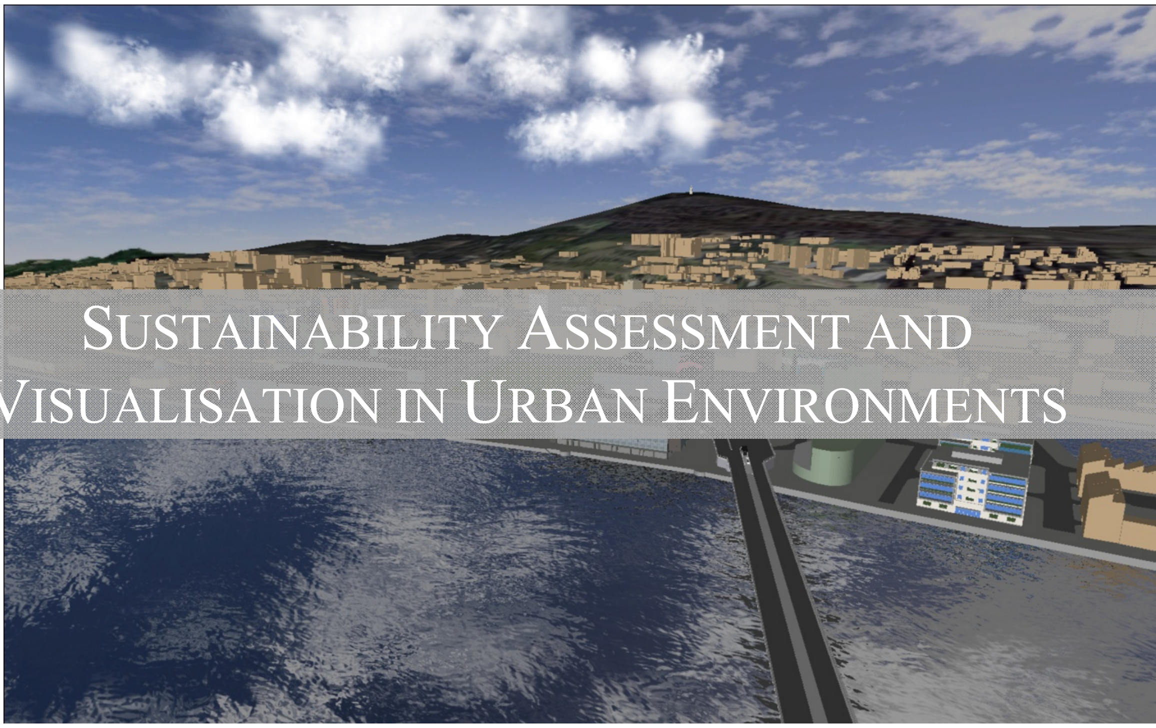
I certify that this thesis is the true and accurate version of the thesis approved by the examiners.

Signed…………………………………………. Date…………………….
(Director of Studies)

Declaration

I hereby declare that this thesis has been composed by myself and that it has not been accepted in any previous application for a degree. The work of which it is a record, is my own, unless otherwise stated. All sources of information are acknowledged by means of references.

John Isaacs



Sustainability Assessment and Visualisation in Urban Environments

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Abstract

This thesis describes a programme of research work which investigated the need for and the development of a novel decision support tool for sustainable decision making in urban environments. The Sustainable City Visualisation Tool (S-City VT) uses a sub-modelling approach coupled with 3D visualisation to support sustainable decision making and has been designed to engage non-expert and expert stakeholder regardless of background or experience in the decision making process. The programme of work describes the rationale, the development and the effectiveness testing of S-City VT using Dundee Central Waterfront as a case study.

An evaluation of existing decision support tools (DSTs) for sustainability is presented and reasons for the lack of uptake and use of these tools is identified. Techniques from DSTs used in other disciplines are also evaluated and those that can be applied effectively in decision making for sustainable urban design are identified.

Based on this review of existing tools and techniques a prototype, interactive simulation and visualisation decision support tool, is created. The novel decision support tool combines sustainability indicator modelling, multi-criteria analysis, scenario design and 3D visualisation in an aim to address the identified weaknesses in existing tools and engage a wider range of stakeholders than is possible using existing sustainability assessment tools.

The performance of the tool and the underlying visualisation techniques are then evaluated for effectiveness and usability with different stakeholder groups, including local authorities and the general public. Finally conclusions are drawn regarding how the project aims are addressed by the S-City VT tool.

Table of Contents

Index of Figures

Index of Tables

Index of Equations

List of Abbreviations

2D	Two Dimensional
3D	Three Dimensional
3DS MAX	3D Studio Max (a graphics package)
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
AUSTIME	Assessment of Urban Sustainability Through Integrated Modelling and Exploration
BEQUEST	Building Environmental Quality Evaluation for Sustainability through Time
BRE	Building Research Establishment
BREEAM	BRE Environmental Assessment Method
CAD	Computer Aided Design
CSA	Community Sustainability Assesment
DST	Decision Support Tool
GIS	Geographic Information System
HUD	Heads Up Display
ISAT	Integrated Sustainability Assessment Toolkit
MAUT	Multi Attribute Utility Theory
MCDA	Multi Criteria Decision Analysis
MDI	Multi Document Interface
PETUS	Practical Evaluation Tools For Urban Sustainability
PhiZ	Phosphate Visualisation
S-City VT	Sustainable City Visualisation Tool
SEEDA	South East England Development Agency
SMART	Simple Multi-Attribute Rating Technique
SPEAR	Sustainable Project Appraisal Routine
STEEDS	Sustainable Transportation Engineering & Environmental Design
SUNtool	Sustainable Urban Neighbourhood Modelling Tool
SUTRA	Sustainable Urban Transportation
VR	Virtual Reality
WCED	World Commission on Environment and Development
XNA	XNA is not an acronym or abbreviation

Chapter 1 Introduction

1.1 The Need for Sustainable Urban Development

The world, especially the developed countries, has become increasingly dependent on its urban centres which provide the basis for a nation's development by controlling the flow of information, energy, commerce and people (WCED 1987). During the 1950s 30% of the world population lived in cities, in 2009 this proportion rose above 50% for the first time. In the most developed areas; Oceania, North America and Europe this has now risen to at least 75% (United Nations 2008). This trend is expected to continue as the world's population increases for both the more and less developed regions as shown in Figure 1.1.

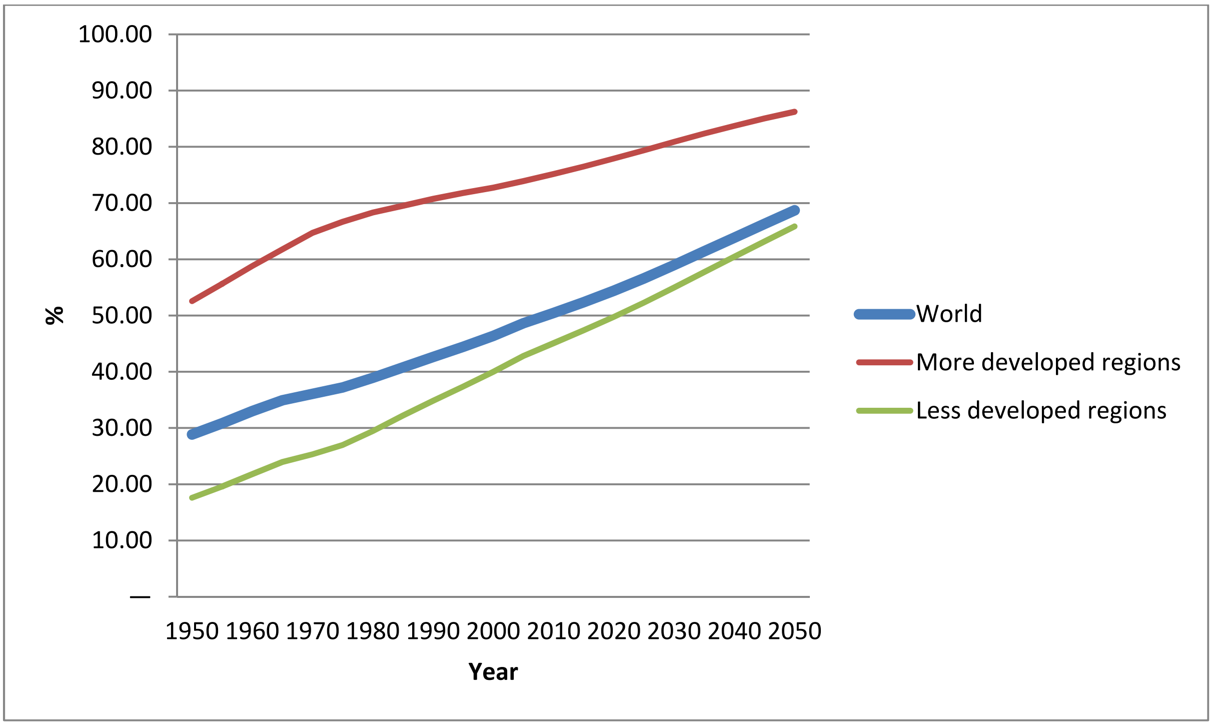


Figure 1.1 Proportions of population living in urban environments, 1950 -2050 (UNDESSA United Nations 2009)

The increase in urban population and our dependency on the urban centres has fundamentally changed the way in which our cities function. Cities were originally “fine grained” or small self contained areas fulfilling industrial, commercial and residential functions. The first major changes in the structure of our cities came in the 19th century with the industrial revolution when large factories became common. These large factories required large residential areas to house the growing numbers of factory workers. Contemporary cities have now become “large grained” in structure, i.e. large zones set aside for specific purposes, with commercial zones usually located in the city centre which are surrounded by low quality, high density residential housing. The large factories have gone, being replaced by industrial estates usually located at the outskirts of the city. Today most cities are now also surrounded by ever-expanding low-density suburban residential areas (Haughton & Hunter 2003). This progression from “small grained” to “large grained” layout is evident in Figures 1.2-1.4, which show how the city of Dundee has changed over the last 180 years. Figure 1.2 shows that the city was mainly based on small areas, highlighted in blue, which spread out along the main roads from the city centre. These small self contained area were usually based around a particular thoroughfare into the city or around the large houses and estates around the city. Figure 1.3 shows how, during the industrial revolution, the city changed to accommodate the influx of workers to the new factories and mills. The main residential areas now surround each of the factories very close to the city centre. Figure 1.4, which shows the layout of Dundee in 2010, shows how the main residential areas are now situated out of the main city centre along with supermarkets and larger stores, close to the main ring roads.

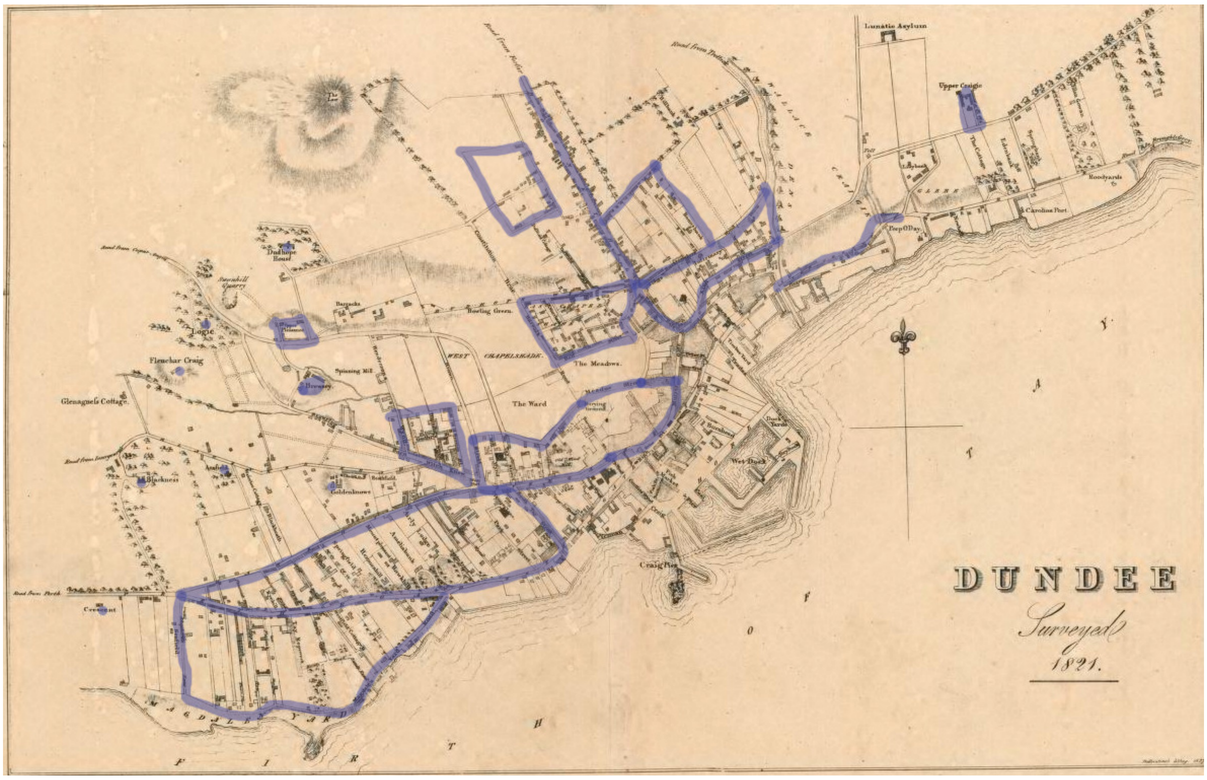


Figure 1.2 Map showing Dundee City in 1821, main areas of work and habitation are highlighted in blue (Wood 1821).

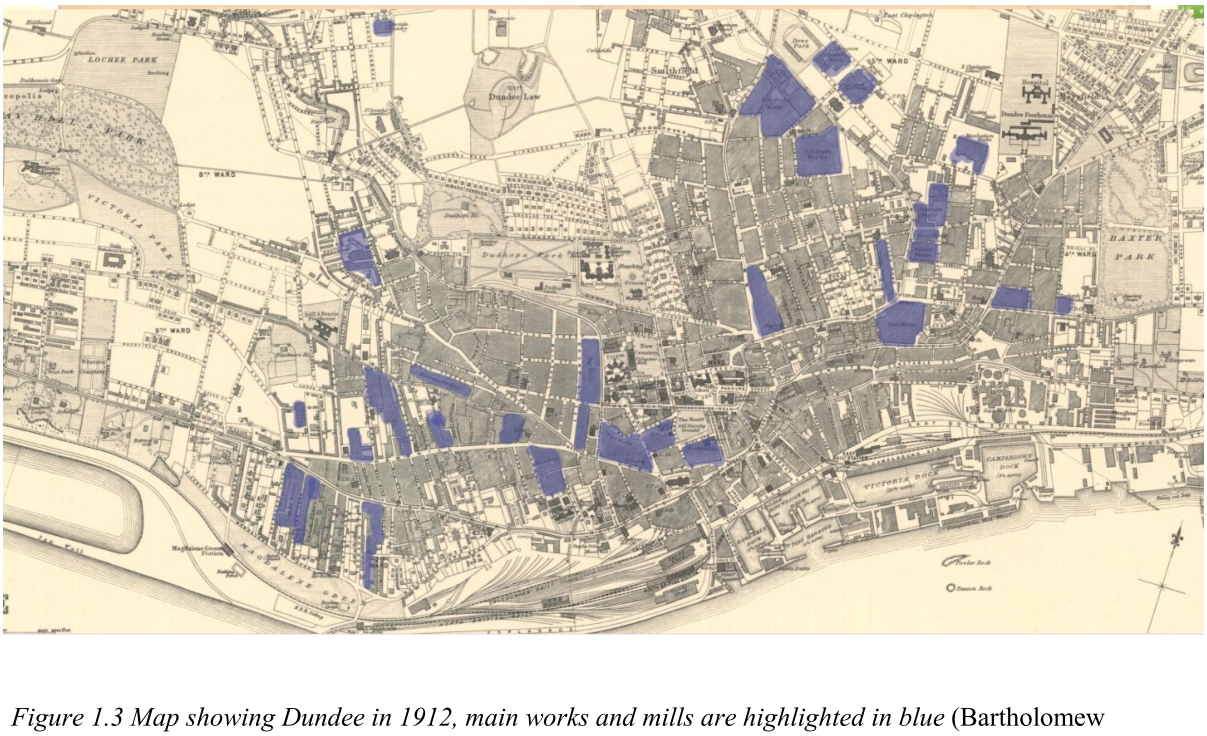


Figure 1.3 Map showing Dundee in 1912, main works and mills are highlighted in blue (Bartholomew 1912).

Figure 1.4 Map showing Dundee in 2010, main commercial centre and supermarkets marked in blue, high density housing highlighted in green (Ordinance Survey 2010).

It is clear that our society has irrevocably changed the structure of the cities in which we live. It is also clear with hindsight that some of the changes we have made are to the detriment of the natural, cultural and social environments (Haughton & Hunter 2003). Examples include historic buildings demolished to build office blocks, open spaces built upon to provide the next generation of suburban homes and shops being placed further away from residential areas in the form of supermarkets and retail parks, increasing the amount of time and energy required to travel from one place to another (Haughton & Hunter 2003).

Our cities continue to grow both economically and physically to attempt to provide the growing number of citizens with the way of life they aspire to. This unchecked growth increases the pressure on public services and natural resources, putting the economic capability of the urban centres in jeopardy by raising living, maintenance and support costs and providing diminished returns (WCED 1987). We now need to ensure that this growth becomes sustainable, by providing more effective and efficient services, maintaining public health and welfare and reducing harmful resource usage, essentially meeting the needs of today's society without reducing the ability of future generations to meet their needs (WCED 1987; Foxon et al. 2002).

1.2 Statement of aims and objectives

While it is now acknowledged that sustainability must be incorporated into urban design at all scales, this is a complex process that requires the consideration of the social, economic and environmental impacts on the regeneration or development area (Figure 1.5). There are a number of potential stakeholders in urban design, ranging from the public and shop owners who will live and work there to the planners and governmental decision makers who will ultimately decide what courses of action are to be taken. All stakeholders will pursue their individual or group interests whether these are on local, national or global scales. This combined with the range of issues, interests and levels of decision making ability of the stakeholders, makes the decision process extremely complex (Scheffran 2006). As effective decision making is dependent on genuine stakeholder contribution during the decision making process, it is vital that all the stakeholders are involved, but the current prevailing practice in urban design is for decision makers to seek agreement for proposals once the key decisions have already been made (Geldof 2005). In particular, engagement with the general public throughout the decision making process presents challenges in communicating not only the complex and interdependent facets of sustainability in decisions, but also in providing an understanding to stakeholders of the short and long term implications of alternative courses of action.

Figure 1.5 The three aspects of sustainability

Sustainable decision support tools (DSTs) have been developed but a major barrier to the development and implementation of tools to support urban design is the complexity of the environment in which decision are made (Bouchart et al. 2002; Ashley et al. 2004; Hull & Tricker 2005). It has also been shown (Sahota & Jeffrey 2005) that these tools may lack the ability to engage all the stakeholders due to their focus on "expert" decision makers (e.g. planners, architects, and design engineers).

It is therefore believed that there is a requirement for new decision support tools that can deal with the complexity of urban design and which go beyond the technical orientation of previous tools (Sahota & Jeffrey 2005) enabling the real inclusion of sustainability in the decision-making processes. A hypothesis is that an essential component of such tools is the application of novel visualisation techniques to aid interaction between stakeholders and to communicate complex datasets. Two dimensional visualisation has been successfully applied to view and analyse a number of factors in the urban design arena, including transportation (Arampatzis et al. 2004; Fedra 2004), goods & markets (Semboloni 2007) and crime (Lodha & Verma 2000). These existing tools tend to concentrate on a single aspect of sustainability, e.g. demographics, pollution or crime. It can be argued that being two dimensional, these tools lack the ability to completely engage the user (Kapelan et al. 2005). Visualisation in three dimensions i.e virtual environments, has the ability to more fully engage the user's perceptual and spatial faculties and aid them in processing the complex information presented (Knight 1998; Pettifer & West 1997; Charters et al. 2002). Previous work on developing virtual environments to aid decision making in the urban (Köninger & Bartel 1998a; Chang et al. 2007) and rural environments (Ball et al. 2007; Miller et al. 2008a) has been performed, however these tools tend to concentrate on a particular aspect of sustainability and use the 3D virtual environment mainly to show the physical representation of the environment.

This project aims to evaluate and identify gaps in existing decision support tools for sustainability and identify where techniques from DSTs used in other disciplines can be applied effectively in decision making for sustainable urban design. Then based on this review to create a prototype interactive simulation and visualisation decision support tool, the Sustainable City Visualisation Tool (S-City VT) that assesses and communicates sustainability information to all stakeholders involved. The performance of the tool and the underlying visualisation techniques will then be evaluated for effectiveness and usability with different stakeholder groups, including local authorities and the general public.

The overall hypothesis of this research has therefore been developed as;

"Can 3D visualisation and modelling be combined into a single decision support tool to effectively support the decision making process and engage both expert and non-expert stakeholders in the development of sustainable urban environments?"

1.3 Methodology

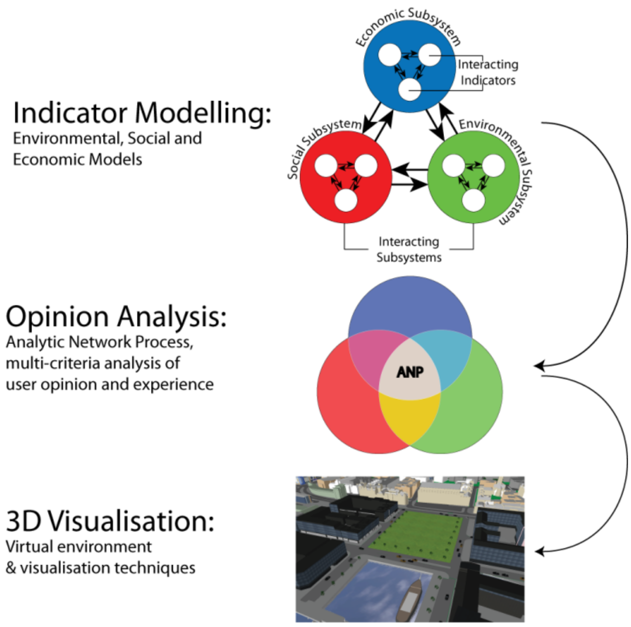


Figure 1.6 S-City VT prototype tool methodology

Existing literature on the use of decision support tools used in sustainability assessment and communication was collated and analysed to indentify if there were gaps in the knowledge base. From the literature, it was identified that barriers to the use of decision support tools, were the lack of understanding both of the complex indicator data used to form the decisions and the underlying complexity of the how the indicators interacted to determine an aggregated measure of the sustainability of a given scenario. It was also clear from literature and examination of existing tools that visualisation could play a role providing a powerful method of presenting the complex information.

Existing tools were identified that provide a visualisation component, however few of these went beyond simply recreating the physical appearance of particular scenarios; those that did concentrated on a specific aspect of sustainability, e.g. pollution or wind farms. The literature review highlighted that a visual decision support tool may be successful in engaging a wide variety of stakeholders, addressing the key aspects of sustainability and also containing visualisation techniques that would display the multivariate sustainability data in a way that would be understood by the different stakeholders. Chapter 2 details the full findings of the literature review.

The Dundee waterfront development was chosen as the case study for the prototype decision support tool (DST). The waterfront project is an urban regeneration development, which started in 2006 and would provide the necessary sustainability data and urban design scenarios. Dundee City Council has identified sustainability indicators which have been and will continue to be measured for the life time of the development projects (~30 years) (Gilmour et al. 2011). This provides an opportunity to parameterise the DST using sustainability indicators that the decision makers have identified as important for the case study. The rationale for the selection of the Dundee waterfront as a case study is detailed in Chapter 3.

A subset of indicators from the set identified by Dundee City Council was then selected to reflect the three aspects of sustainability, environment, society and economy. Two indicators were selected from each pillar of sustainability: housing provision and acceptability from social, economic output and employment from economic and energy efficiency and noise pollution from environmental. For each indicator the spatial and temporal changes were predicted by a computational model. The sub model behaviours are informed by collected data, data from existing sources such as EUROSTAT (the European statistics database) or existing models such as the national calculation method used for the energy efficiency indicator. The computation models and their implementation are presented in Chapter 4.

Using the sub-models a sustainability assessment can be carried out by assigning weights using multi-criteria decision analysis techniques, namely the analytical network process. The ANP method allows the stakeholders (users) to transparently apply their own experience and knowledge to the sustainability decision. The implementation of the ANP process is presented in Chapter 5.

The review of sustainability assessment methods highlighted there is little use of 3D visualisation for assessment and communication of urban sustainability. From the success of visualisation used in areas other than sustainability, which allow users to explore physical appearance and information associated with the domain, it is evident that 3D visualisation could provide not only a clear method of representing the urban environment, but also be an immersive and engaging tool. A custom Visual DST was designed which would enable the coupling of the indicator modelling and the 3D environment with custom visualisation techniques in real time. The visual DST has a custom 3D engine as a component which is based on programmable pipelines for graphics rendering. Microsoft XNA was chosen as the development framework to create the DST, XNA utilising the .Net framework to allow the greatest flexibility due to its cross language infrastructure. No existing "off the shelf" software could be used for the development of the visual DST. The reasons for this are twofold; existing graphics packages may allow creation of novel and flexible visualisation techniques but they prohibit real-time updates from computational models. Many existing solutions also require expensive specialised hardware and software to perform these functions.

Digital terrain maps, sourced from NASA's satellite radar topography mission and digital elevation maps, sourced from Dundee City Council were used to create the 3D representation of the physical landscape of Dundee waterfront and its surrounding areas. Dundee City Council also provided 3D models of the proposed buildings and 2D plans of the proposed plot and road layout for the waterfront regeneration development. These were imported into the DST to create a representation of the regenerated waterfront. The DST was designed to allow the proposed building's position and outward appearance to be changed allowing for different scenarios to be explored. Chapters 6 & 7 cover the implementation of the scenario development and 3D rendering components respectively.

To verify the viability of the 3D representation, a small study was performed where the participants were shown a selection of glass and brick buildings using real (photographic) and virtual (on the 3D virtual environment) representations, their preference for specific building types, i.e. glass or brick, was recorded. The study (Chapter 7 page 141) showed that there was no difference in the participant's preferences regardless if the buildings they were shown were real or virtual. These findings support the use of the virtual environment in displaying the appearance of possible scenarios by showing that people's preferences were unaffected by the virtual representation.

Existing visualisation techniques were then identified that would enable the results of the sustainability assessment (sub-model and ANP weighting) to be displayed on the 3D virtual environment. These visualisation techniques are detailed in Chapter 8.

The visualisation techniques selected were tested on stakeholder groups to determine their effectiveness and suitability for each group. A focus group approach was used as this reflects the group decision process with which most sustainability planning decisions are made. The tests were designed to determine if the stakeholders were able to decide based on the different visualisation techniques which of the scenarios were relatively more sustainable. The overall usability of the Visual DST (S-City VT) was tested to determine if stakeholders were able to perform the abilities provided by the tool: navigation and scenario development for example. The tests and their results are detailed in Chapter 9.

1.4 Summary of key findings

The key findings of the thesis were that currently there are no sustainability assessment tools which holistically address sustainability and attempt to engage non-expert stakeholders. It was also identified that 3D virtual environments combined with visualisation techniques used in other disciplines could be used to engage more users in decision making. The development of S-City VT showed that it was possible to combine sustainability indicator modelling, multi-criteria analysis and 3D visualisation to create a single tool which crosses the traditional decision support tool categories (model based, visual based, ranking based or process based). Finally it was shown that a tool which combines these components can effectively support decision making and begins to remove the emphasis on expert stakeholders by engaging experts and non-experts alike.

Chapter 2 Sustainability Assessment & Decision Support

2.1 What is Sustainability?

In 1987 the World Commission on Environment and Development (WCED 1987), stated that “Humanity has the ability to make development sustainable to ensure that it meets the needs of the present without compromising the ability of future generations to meet their own needs”. Out of the many definitions of sustainability this profound statement has become the most widely accepted (Kates et al. 2005). It is what these needs are, how we impact upon them and how our impact can be measured or assessed that raises the most debate (Parkin et al. 2003). Sustainability can be described as a quality which something has. Sustainable development can subsequently be defined as the process over time whereby sustainability is achieved. It is the aim of sustainable urban development to provide “more effective and efficient services which maintain public health and welfare, whilst reducing harmful resource and environmental impacts” (Foxon et al. 2002).

Sustainability is often symbolised using three overlapping circles (Figure 2.1), representing the three aspects of sustainability (society, economy and environment). However this simple diagram over simplifies the complex interactions which occur between the aspects and the large number of indicators which are used to measure impact. The contemporary emphasis on sustainability has changed the nature of decision making as any decision made will have to include these complex economic, social and environmental considerations (Sahota & Jeffrey 2005). Unless the results of these complex interactions are understood by the stakeholders, it would be impossible to fully assess the sustainability of any development (Foxon et al. 2002).

Figure 2.1 Three aspects of sustainability

Sustainability is measured using principles, criteria and indicators (Defra 2005). Principles are usually abstract, idealistic statements that provide goals in order for sustainability to be achieved. Criteria are a set of factors which can be used to make a judgement about the relative sustainability of a number of options or scenarios. Indicators are measurable past and current values for specific criteria and can also be used to set standards against which future performance can be assessed. It is usual for criteria, and the indicators used to measure them, to change quickly, however, the principles on which the criteria are based usually remain fixed (Foxon et al. 2002).

In March 2005 the Secretary of State for Environment, Food and Rural Affairs released a new document, "Securing the Future" which outlined a new set of sustainability principles. It is these new principles, and the 68 new indicators associated with them, which the Government, the National Executives (Scottish, Welsh and Northern Irish assemblies) and local councils will use to gauge the sustainability of any development projects (Defra 2005). These principles have since been updated to those shown in Figure 2.2. These principles will also form the basis upon which development project decisions will be based.

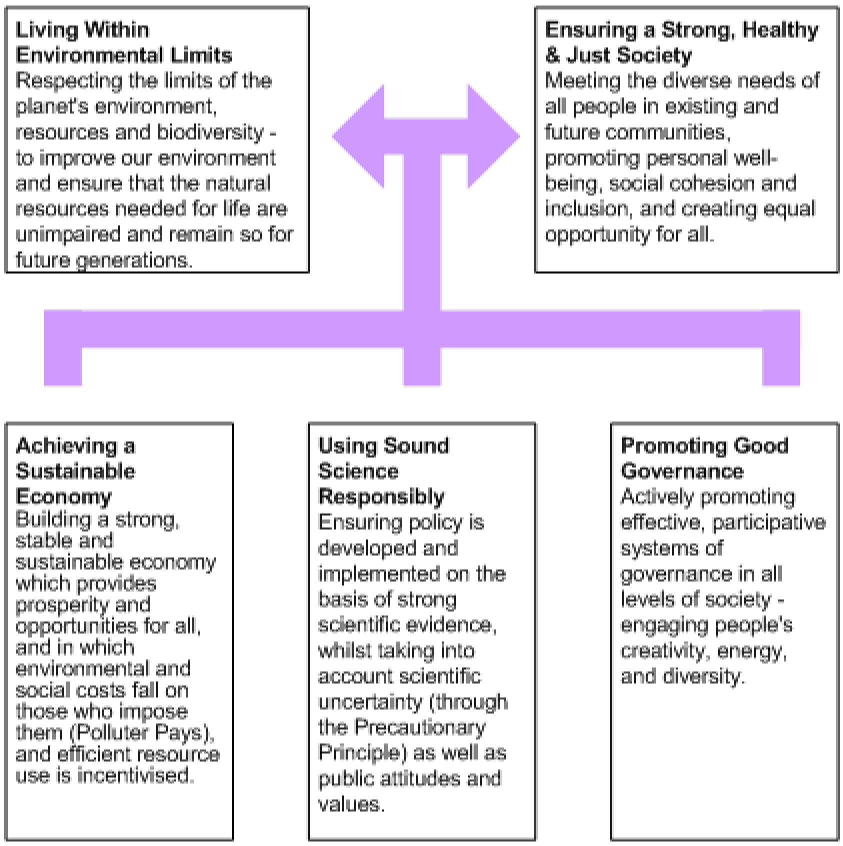


Figure 2.2 UK Government Sustainability Principles (Defra 2011)

Sustainable development is also "a fundamental objective of the European Union under the Lisbon Treaty" (European Commission, 2010). The European Union set out a number of key principles for their sustainability strategy, these are summarised below;

- PROMOTION AND PROTECTION OF FUNDAMENTAL RIGHTS;

  Reduce discrimination and poverty and eliminate social exclusion.

- SOLIDARITY WITHIN AND BETWEEN GENERATIONS;

  Address the needs of current generations without compromising the ability of future generations to meet their needs.
- OPEN AND DEMOCRATIC SOCIETY;

  Guarantee citizens' rights to information and develop consultation and participatory channels for all interested parties.
- INVOLVEMENT OF CITIZENS;

  Enhance participation of citizens in decision making and promote and inform the public about sustainability and their impact on the environment.
- INVOLVEMENT OF BUSINESSES AND SOCIAL PARTNERS;

  Foster cooperation and common responsibilities to achieve sustainable consumption and production.
- POLICY COHERENCE AND GOVERNANCE;

  Promote coherence between all European Union policies and coherence between local, regional, national and global actions.
- POLICY INTEGRATION;

  Promote integration of economic, social and environmental considerations by making full use of instruments for better regulation, such as balanced impact assessment and stakeholder consultations.
- USE BEST AVAILABLE KNOWLEDGE;

  Ensure that policies are developed, assessed and implemented on the basis of the best available knowledge and that they are economically sound and cost-effective.
-

- PRECAUTIONARY PRINCIPLE;

  Where there is scientific uncertainty, implement evaluation procedures and take appropriate preventive action in order to avoid damage to human health or to the environment.

- MAKE POLLUTERS PAY;

  Ensure that prices reflect the real costs to society of consumption and production activities and that polluters pay for the damage they cause to human health and the environment (Council of the European Union, 2006).

It can be seen that the UK Government and the Council of Europe have different principles by which they define sustainability, although the UK's smaller set of principles do fit well with the set defined by the EU. Both the EU's and UK's principles fit within the overall pillars of sustainability addressing the social, environmental and economic aspects.

The programme of research presented here addresses many of the sustainability principles proposed by the Council of Europe and the UK Government (Figure 2.2). The main aims of the project are to develop a decision support tool (DST) which allows the sustainability assessment of development projects within all three pillars of sustainability (Figure 2.1). The DST will be developed to better inform and engage the public in sustainability issues and to increase their participation in the decisions made. This clearly fits well with the EU's "Open and Democratic Society", "Involvement of Citizens" and "Involvement of Business and Social Partner" principles and also with the UK's "Promoting Good Governance" principle.

2.2 Decision support tools for sustainability

A decision support tool (DST) is simply any tool which is used to aid decision making as part of a formal or informal decision-support process. The use of DSTs has become increasingly more popular, mainly because it is possible to install and use them on many personal computers and also due to their ability to manage large amounts of complex data (Kapelan et al. 2005).

A number of decision support tools have been created to address the complex issues involved in sustainable development decisions. There has been huge effort and investment into creating decision support tools, yet despite this most are never or hardly ever used (Sahota & Jeffrey 2005).

There are a number of reasons for this lack of uptake, usually the decision support tools are designed for a single purpose, to investigate transport issues for example, or that the systems become so generic that any detailed results are lost. As many decision support tools are created but are not widely used it can be difficult to determine their effectiveness as there is little evidence of how they have been used in practice.

Kapelan et al. (2005) outline a number of criteria which any decision support tool should have to overcome the problems of lack of uptake and use. These criteria for an effective DST for sustainability decisions are summarised below;

High level of integration across different domain criteria and indicators.

A DST should provide a holistic approach by dealing with the environmental, social and economic domains of sustainability to allow the sustainability of any decision to be effectively described.

Detailed impact assessment of proposed action and developments.

This allows stakeholders and decision makers for the development being assessed to determine the social, economical and environmental impacts of decisions they make before the real development is created.

Allow modelling of possible future urban scenarios.

A DST should be able to predict the effect of specific scenarios on the decisions made. Some generic scenarios should be built into the model, however it is important that the user is able to add their own custom scenarios, as it is unknown now what new scenarios could happen to affect developments in the future.

Include pre-built policy options, government & council laws or guidelines.

The government or local council could also change policy on any number of issues throughout the life time of a development, a city wide recycling policy for example. The DST must be able to cope with any effects these policies could have on a development.

The user should be able to select the most sustainable scenario or solution.

As there will be a range of possible solutions to a specific decision, the DST should be able to allow the user to identify the 'best' solution depending on the indicators used.

Calibrated and validated using sufficient quantity/quality of observed data.

To ensure the accuracy of the model the indicator values and other data used in its creation must be real world past and present values.

Should be as (computationally) efficient as possible without reducing usefulness.

The model should also remain as flexible, efficient and accurate as possible without detracting from its usability. It is of no use if the model takes ten days to model a five minute period in the real world.

Include 3D/virtual reality visualization techniques.

The DST should provide the user with a 3D representation of the development enabling the stakeholder to determine the effects of decisions made in a real-life context. Not only is it important that the stakeholders can view the impacts of their decisions in a real-world context through the use of 3D, it is just as important that the decisions can be seen in real-time.

Provide spatial and temporal scales.

The DST should also provide the user with the opportunity to see how their decisions and scenarios affect the sustainability of the wider area, such as the entire city. With this in mind, the interface should provide the user with the possibility of selecting different spatial and temporal scales in which the impacts of the decision can be seen.

Include a 'rich', graphical user interface to allow use by non-experts.

The complex functionality being developed will be of no use to the stakeholders if they are unable to access and understand how to use it. It is extremely important that the DST contains a simple but effective graphical user interface which will allow people not familiar with the system to be able to use it and to gain a valid, meaningful result.

Possibility for group decision-making and communication.

It is also believed that the inclusion of a collaboration component be added to the visualisation tool as this will allow stakeholders, who cannot all be present at the same place or time, to discuss the possible solutions and decisions made.

Kapelan et al. (2005) suggest that, when written, there was no tool that successfully fulfilled these criteria and that any new decision support tool would need to fulfil all these criteria to be effective. Khandokar et al. (2009) and Paranagamage et al. (2010) highlight that this problem still exists and that no fully holistic tool that is available and accessible for all users yet exists. In a report by BRE (2004) and in Ness et al. (2007), where tools have been categorised in to groups based either on their format, purpose or stage of application, this categorisation highlights the lack of a single integrated tool. Examples of existing decision support tools within the categories, based on those outlined in BRE (2004), are included in the following section.

2.2.1 Process Based

Process based decision support tools are mainly frameworks or checklists which show the steps which should be taken in a sustainability assessment. Framework based tools organise existing references, analysis, benchmarks and case studies and use these to provide a policy of actions. Checklist tools similarly use existing sources to provide the user with a series of steps which should be completed or to provide a score for a proposed development (PETUS 2005). They are not necessarily software tools and can simply consist of a flow chart describing the necessary steps. For example the BEQUEST (Building Environmental Quality Evaluation for Sustainability through Time) toolkit is a modular system designed "to support the decision maker concerned with urban sustainability" (Hamilton et al. 2002; Bequest 2001). The toolkit is composed of 4 modules: protocol, assessment methods, advisors and glossary.

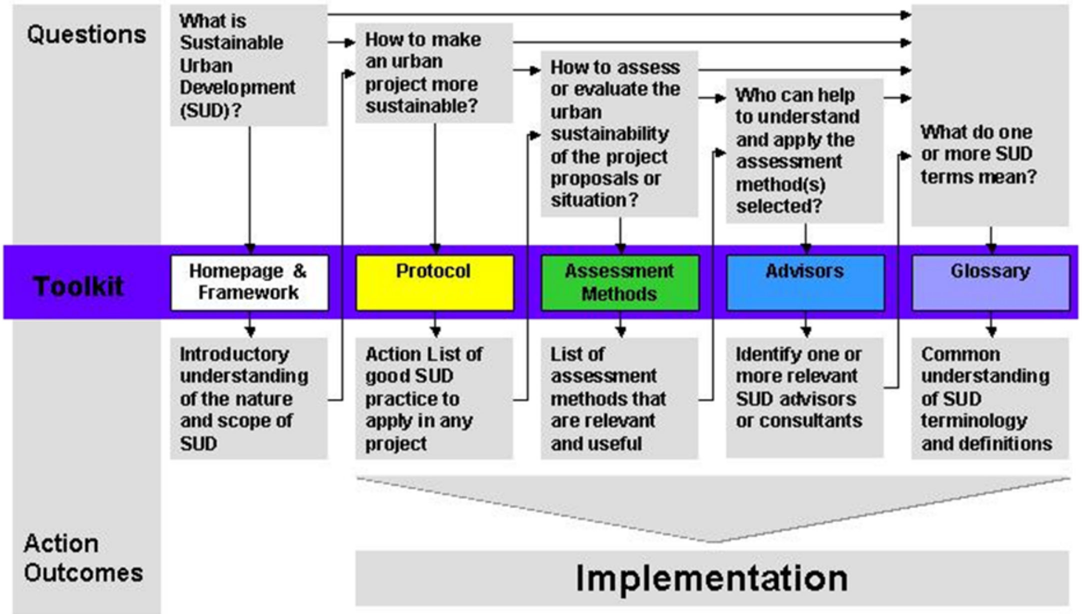


Figure 2.3 Bequest user model (Bequest 2001)

BEQUEST is a web-based system which provides generic information about sustainable development (Figure 2.3). The toolkit provides the users with textual results such as assessment techniques which can be used to examine the development at different stages or a list of advisors who could advise about the relative sustainability of a specific part of the development. When compared to the criteria suggested by Kapelan et al. (2005) the toolkit provides a good level of integration across the problem domains; however it does not contain any scenario, impact analysis or policy options.

The BRE Sustainability Checklist for developments is a checklist based DST, originally released in paper form (Brownhill & Rao 2002) and now available online (SEEDA 2011), that considers environmental, social and economic aspects for planning sustainability into new developments (BRE 2011c). Primarily designed for developers, the checklist provides the user with a number of questions under a range of headings, such as climate change, community, transport, ecology, etc, to enable the developer to determine if their plan is sustainable (SEEDA 2011). The BRE checklist was developed with local authorities and can be modified to suit local or regional developments (BRE 2011c) and it is also suggested by Jensen & Elle (2007) that the tool has been peer reviewed by experts, which provides confidence at all decision making levels. However this expert orientated approach means that the checklist may not be accessible to non-experts.

The Community Sustainability Assessment (CSA) checklist is another checklist tool, however unlike the BRE tool is has primarily been designed for communities. The CSA tool asks the user a number of questions about their community under the different headings of economical, social, ecological and spiritual, then provides a score which allows the user to determine how sustainable their community is (CSA 2010). By addressing all the aspects of sustainability and providing a simple sustainability score, as well as being designed for communities the CSA checklist may allow more stakeholders to become engaged in the assessment process.

Many checklist and framework orientated DSTs by their nature do not provide any visual method of data input or resulting output, which could reduce their ability to engage many expert and non-expert users. Checklists in particular could become laborious if they were developed for many different scenarios. The BRE checklist, for example has over a hundred questions which are quite technical in nature, and could also be extremely subjective if the user does not fully understand the question. These types of tools do not really lend themselves to group decision making, with checklists usually being filled in by one person, however with the CSA checklist a score could be averaged across a wide range of community members to provide a group decision. None of the these checklist tools would seem to satisfy the criteria suggested by Kapelan et al. (2005).

El-Haram et al. (2007) demonstrate a framework based tool, ISAT, which has been developed as a software tool created as an output of the SUE-mot project (SUEMoT 2011).

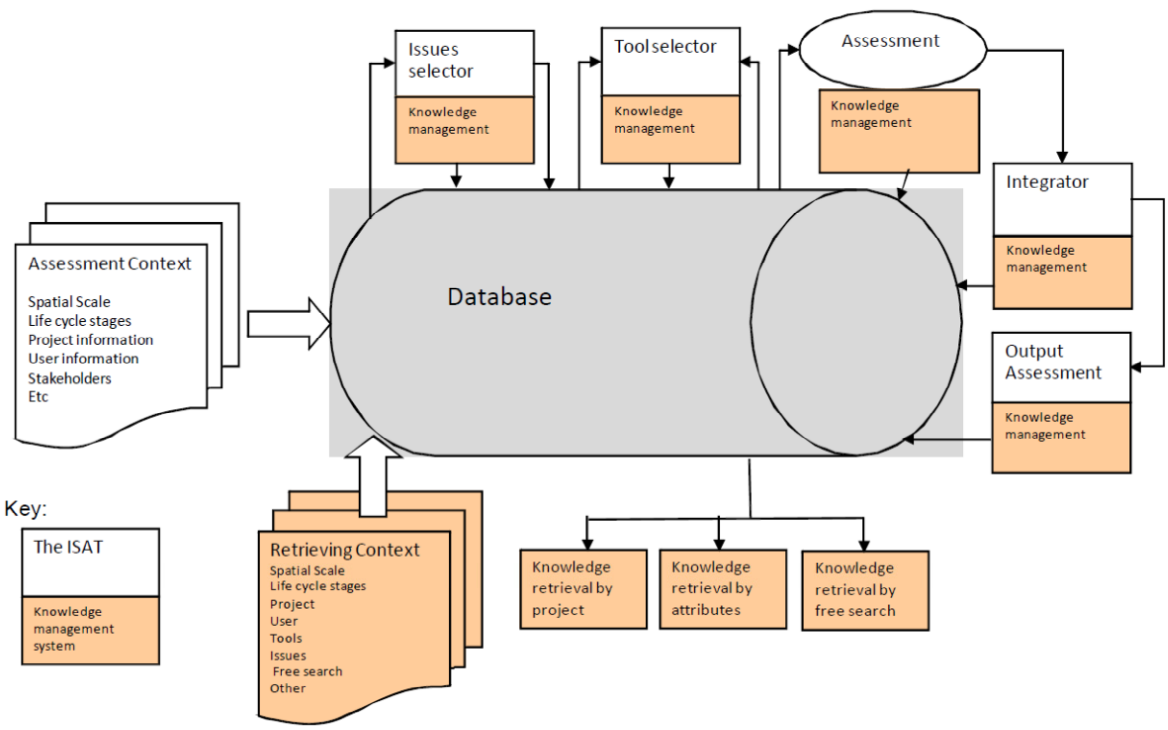


Figure 2.4 SUE-MoT knowledge management system (ISAT) (El-Haram et al. 2007)

The ISAT system is split into a number of stages, shown in Figure 2.4. At each stage the system is able to suggest existing tools, guidelines, codes and procedures that can support and facilitate that particular stage. ISAT also recommends stakeholder identification and engagement tools which may be applicable. The output from each of the activities at any of the stages can be stored in the database providing an accessible record for future consideration (El-Haram et al. 2007).

While the ISAT tool attempts to provide a holistic DST by suggesting and providing access to many of the available existing DSTs, it does rely on the ability of these existing tools to provide the stakeholder with the desired functionality. This entails that any functionality which is lacking, eg non-expert engagement, scalability or constrained sustainability aspects in the existing tools, will also be lacking in any assessment using ISAT (Paranagamage et al. 2010).

2.2.2 Model Based

Model based decision support tools are based on a mathematical or simulation modelling approach to defining sustainability. The use of modelling in general allows DSTs to represent, describe, analyse and simulate the major processes in involved in the problem domain (Campen 2008). In the case of sustainability modelling most of these models are concerned with either socio-economic aspects, such as general economy, or environmental aspects, such as climate change (Campen 2008), although there are some which attempt to provide a more integrated approach.

STEEDS is a “Decision Support System able to assist the policy makers in exploring the influences on market take-up of different transport technologies” (Brand et al. 2002). Steeds is based around a set of scenario and policy options, combined with five interacting subsystem models, with the results of the model being collated as a set of alternatives (Figure 2.5). The alternatives provided by the model can then be investigated in graphical form (data visualisation) or evaluated using multi-criteria analysis (Brand et al. 2002).

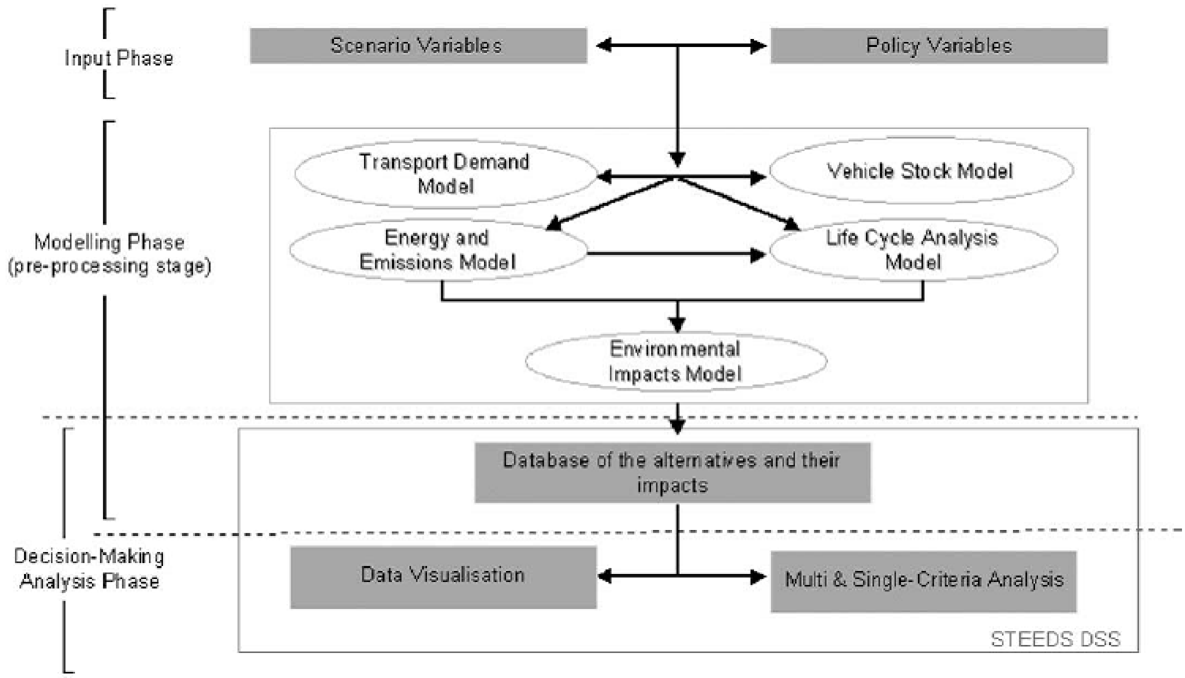


Figure 2.5 STEEDS system model (Brand et al. 2002).

Although the subsystems approach STEEDS implements provides extensive scenario and policy options coupled with impact analysis, these are based solely on aspects of the transport sector. Given that this tool was designed for transport developments, it would be difficult to apply it to urban sustainability which needs to address a wide range of environmental, social and economic aspects. The tool attempts to provide a visualisation aspect through the use of graphs with which the scenarios can be compared, however this does not really constitute the rich graphical user interface or visualisation component which, as suggested by Kapelan et al. (2005), would increase stakeholder engagement.

The Assessment of Urban Sustainability Through Integrated Modelling and Exploration (AUSTIME) methodology was designed to combine "systems analysis, sustainability assessment based on system thresholds and multiagent simulation for scenario exploration" (Daniell et al. 2005). The methodology describes how to create a decision support system to provide sustainability assessment of a specific scenario.

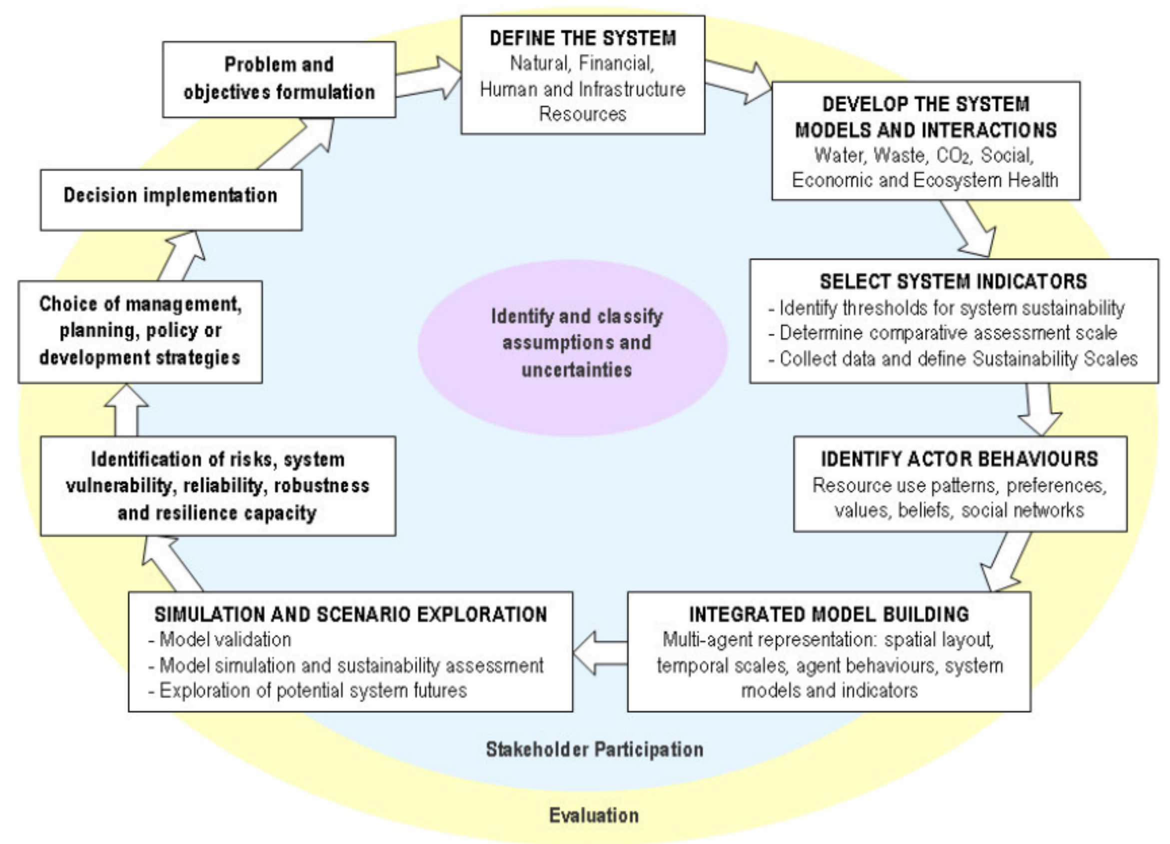


Figure 2.6 AUSTIME development methodology (Daniell et al. 2005).

AUSTIME (Figure 2.6) was used to create a prototype model and perform a sustainability assessment of a development in Adelaide, Australia called Christie Walk. The model produced contained six sub-system models (water, CO_2, waste, ecosystem health, economic and social) each of which could act independently to simulate their respective aspects. The sub-systems were then combined to create a single integrated model which could simulate the sustainability of the development as a whole. The results of the prototype's application to the Christie Walk development were used to show, using graphs, what affects changes in some of the sustainability aspects, water use or CO_2 output for example, would have on the developments over-all sustainability (Daniell et al. 2005).

The prototype created using the AUSTIME methodology for the Christie Walk case study effectively simulates the sustainability of the development for the aspects which were included in the model. The prototype however was weighted towards environmental aspects possibly due to the fact that the Christie Walk development was specifically designed to "demonstrate the vision for an ecological city" (Daniell et al. 2005). The prototype used 6 indicators, one in each subsystem, and allowed the simulation of changes in these indicators within a fixed development. As the development is fixed, the results and impacts of the decision are not immediately obvious to the user and they would need to have prior knowledge of the effect of the indicators before they could fully determine their combined impact. AUSTIME still seems to be a communication tool for the developer or expert stakeholders to determine the sustainability of a set plan and not a tool which allows non-expert stakeholders to become involved in the process, which is necessary in a fully sustainable development (Sahota & Jeffrey 2005).

Integrated transport and land use models have also been used to determine the sustainability of planning decisions; systems such as SPARTICUS and PROPOLIS, have been designed to simulate land use and transport demand change in urban areas (Maoh & Kanaroglou 2009; European Commission 1998; Spiekermann & Wegener 2004). These systems take a large number of sustainability indicators across the range of social, environmental and economic aspects and, as such, are well integrated between the pillars of sustainability. The weights of the indicators used in SPARTICUS and PROPOLIS are determined by an expert group. These weights are then applied to the indicators to provide a sustainability index for each pillar of sustainability and an overall sustainability index for each scenario (Maoh & Kanaroglou 2009). The weighting of the indicators by an expert group could mean that non-expert stakeholders, those not involved in the weighting process, could feel excluded or that their feelings about what is important is being "washed out" by the experts. This does not fit with the findings of Sahota & Jeffrey (2005), Geldof (2005) and Scheffran (2006) who suggest that all stakeholders should be involved in the decision making process.

2.2.3 Rating Systems

Rating systems are designed to provide a standardised system where the user can obtain a value or range of values with which they can compare their building or development with any other which has undergone the same ranking assessment.

The Building Research Establishment Environmental Assessment Method (BREEAM) was the first commercially available environmental assessment tool (BRE 2011a; Grace 2000). Released in 1990, BREEAM aimed to provide the users with a comprehensive means of assessing a broad range of environmental considerations in buildings (Haapio & Viitaniemi 2008), including management, energy use, health and well being, pollution, transport, land use, materials, ecology and water (BRE 2011b). A building which has been "BREEAMed" is provided with a certificate representing how well the building performed in the assessment, either a pass (lowest grade), good, very good, or excellent (highest grade) (BRE 2011b; Grace 2000). BREEAM provides a good method of allowing developers to compare possible solutions by providing a standardised value by which the different options can be compared and it has the ability to be used globally allowing the comparison of buildings all over the world. However BREEAM make clear that their target users are the expert-decision makers, planners, property agents, design teams and building managers (BRE 2011a; Grace 2000). BREEAMs own documentation also states that it "enables developers, designers and building managers to demonstrate the environmental credentials of their buildings to clients, planners and other initial parties". This shows that it has not been designed to engage stakeholders in the initial process but to present the designs once the initial decisions have already been made, which has already been highlighted as a major problem in current sustainability assessment (Geldof 2005). BREEAM is also primarily designed to reflect the environmental aspects of a building and does not cover all of the pillars of sustainability. The certificate provided by BREEAM allows the buildings comparison to any other assessed building, however the reasons for awarding the certificate may not be evident to the non-expert and this may lead the stakeholder to feel excluded from the process.

The ARUP Sustainable Project Appraisal Routine (SPEAR) is a similar ranking technique to BREEAM, but attempts to overcome some of BREEAMs limitations by addressing more sustainability issues and providing a more visual output. First developed in 2000, a SPEAR assessment addresses all the pillars of sustainability based on key themes such as transport, biodiversity, culture, employment and skills (Figure 2.7)(ARUP 2011; McGregor & Roberts 2003).

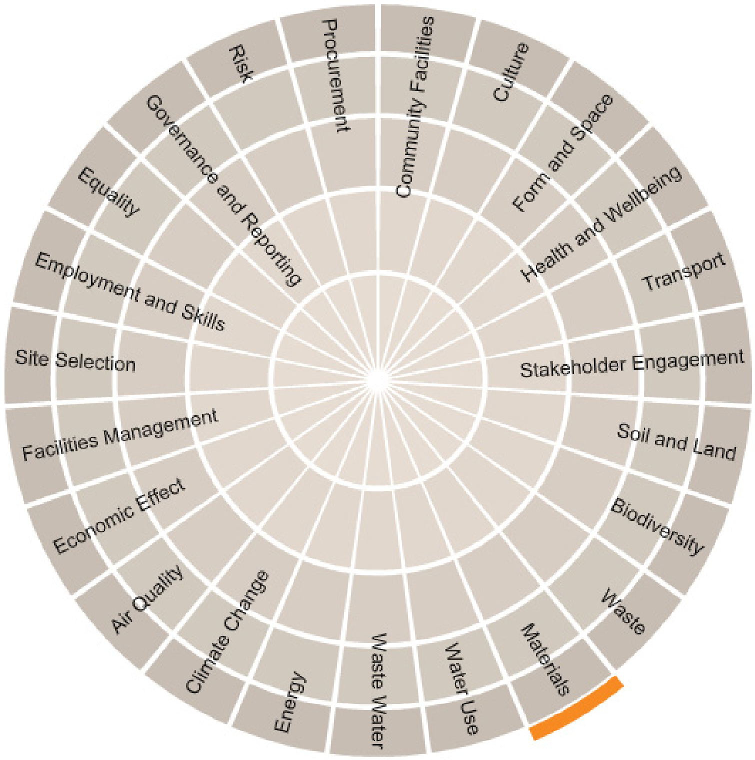


Figure 2.7 SPEAR indicator themes (ARUP 2011)

Updated in 2011, SPEAR has been made more flexible, allowing the addition of various indicators to the original set, and can now take into account indicators produced from other modelling and ranking techniques such as BREEAM (ARUP 2011). SPEAR outputs use a traffic light system (Figure 2.8) which allows each development to have a graph which is comparable to any other development assessed under the process.

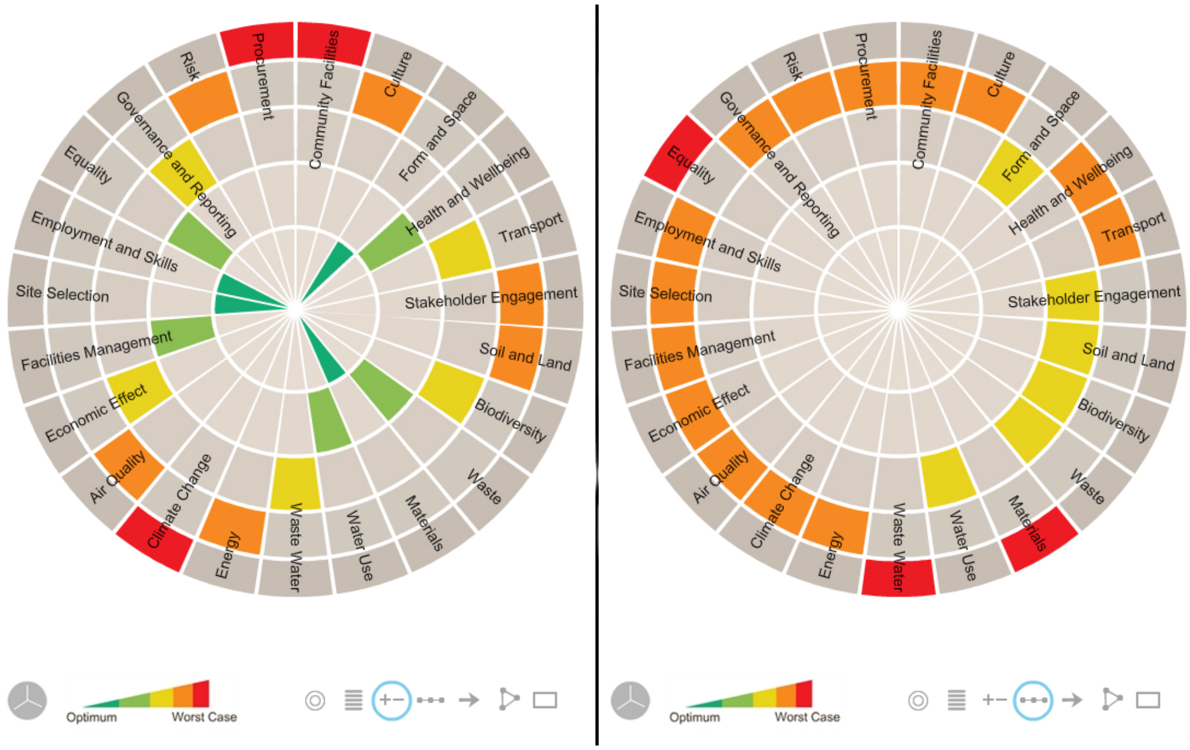


Figure 2.8 SPEAR traffic light system (ARUP 2011)

SPEAR clearly addresses sustainability more fully than other ranking tools and attempts to make the assessment more visual by providing the radar graphs using a simple, recognisable traffic light system. It has, however, been suggested that the units of measure are too general and could give a distorted view of how sustainable a development is (Karol & Brunner 2009). Like BREEAM, the SPEAR assessment also depends on the team assessing the development and sub criteria weights may vary by assessment or context (Karol & Brunner 2009). This lack of transparency can affect how accepted the tool is by non-expert stakeholders and, like BREEAM, SPEAR seems to be more designed for expert stakeholders to show the green credentials of their already designed buildings rather than to aid discussion in the design process. It has also been suggested Jensen & Elle (2007), that ranking DSTs providing certificates may not increase the sustainability of a building or development as the building has already been designed and that the developer would have acted the same had the assessment not been performed.

2.2.4 Visual Based

“The primary objective of SUTRA is to develop a consistent and comprehensive approach and planning methodology for the analysis of urban transportation problems, which helps to design strategies for sustainable cities” (SUTRA 2006). SUTRA is a web-based (Figure 2.9) system which uses an indicator based simulation model combined with social, environmental and economic impact analysis (SUTRA 2006). Similar to STEEDS, SUTRA provides the user with extensive scenario and impact analysis support, however Sutra’s main advance over other decision support systems is the way in which the results are presented to the user.

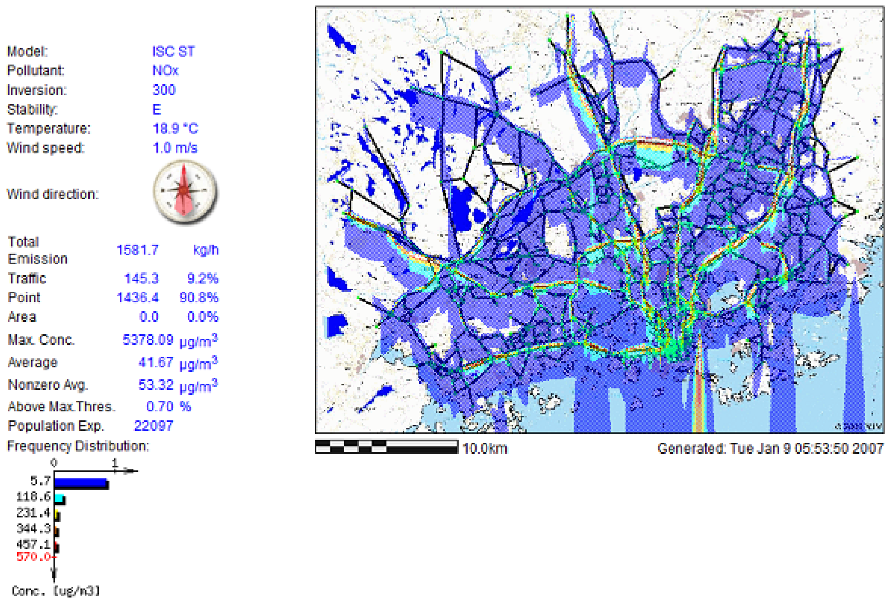


Figure 2.9 SUTRA Simulation Screen (SUTRA 2006).

Using SUTRA, the user is no longer presented with more complicated graphs or tables but instead can view the impact of decisions they have made in real-time, projected on a two dimensional map of the area or city being investigated. Figure 2.9 shows an example simulation of NOx (Nitrogen based pollutant) release from traffic in Helsinki.

This approach of animated, visual results opens the system to use by non-expert stakeholders, e.g. the general public.

The Sustainable Urban Neighbourhood Modelling Tool (SUNtool) has been created to assist in the design of more sustainable urban neighbourhoods based on accurate simulations of resource (energy , water and waste) flows (Robinson et al. 2007). SUNtool concentrates on the environmental aspects of sustainability using a sub modelling approach to calculate the impact of different building options within the neighbourhood (Figure 2.10).

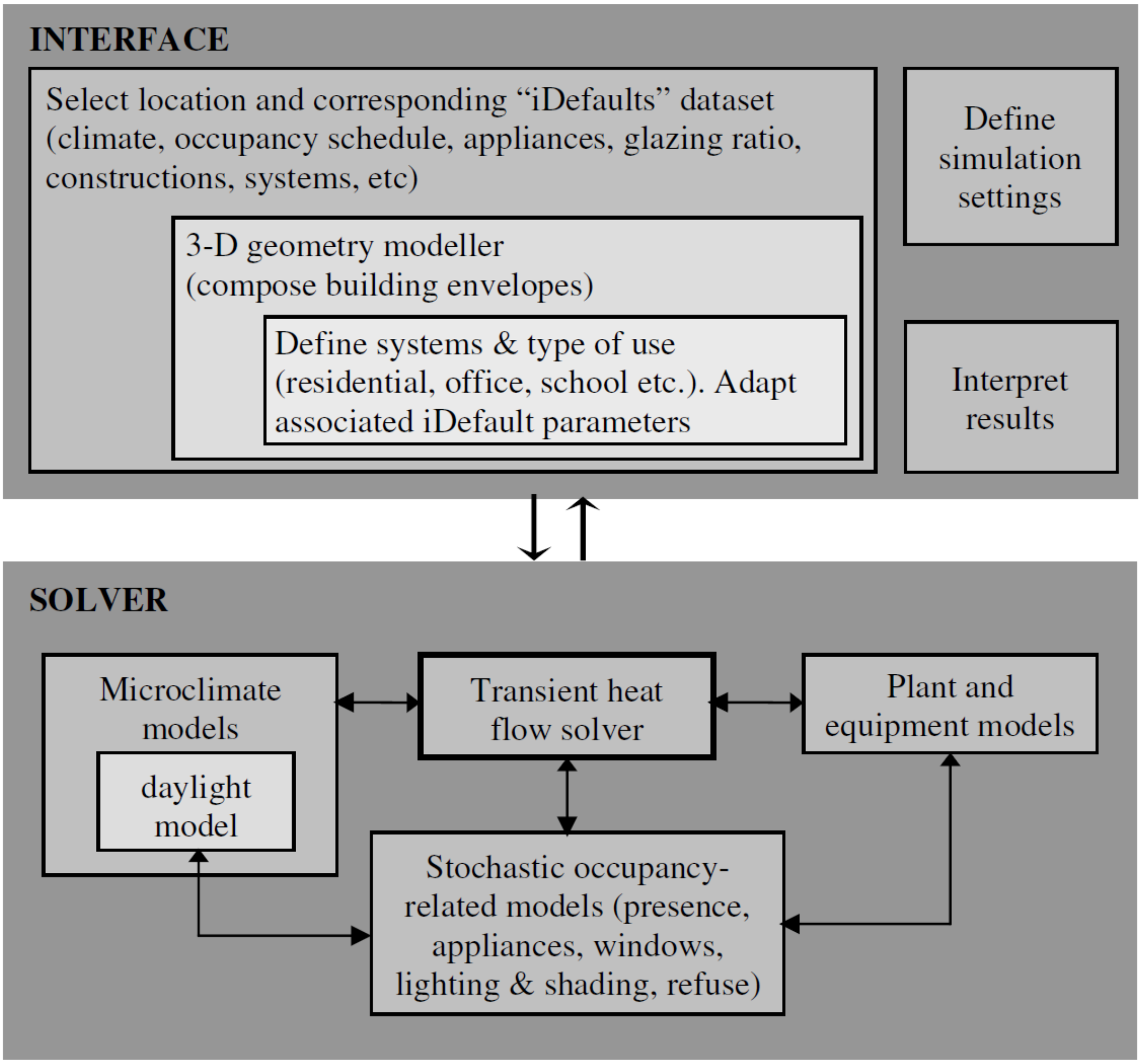


Figure 2.10 Conceptual model of the SUNtool DST (Robinson et al. 2007).

SUNtool allows the user to develop 3D models from CAD floor plans or import simple 3D models from CAD software. It then projects the sustainability information onto these models as well as displaying data more traditionally using graphs. SUNtool does include a rich GUI which includes a 3D visualisation component, however 3D models used by SUNtool are very low in detail and the development is visualised without a surrounding urban context (Figure 2.11) so this may not allow a non-expert stakeholder to fully understand the context of the decisions being made.

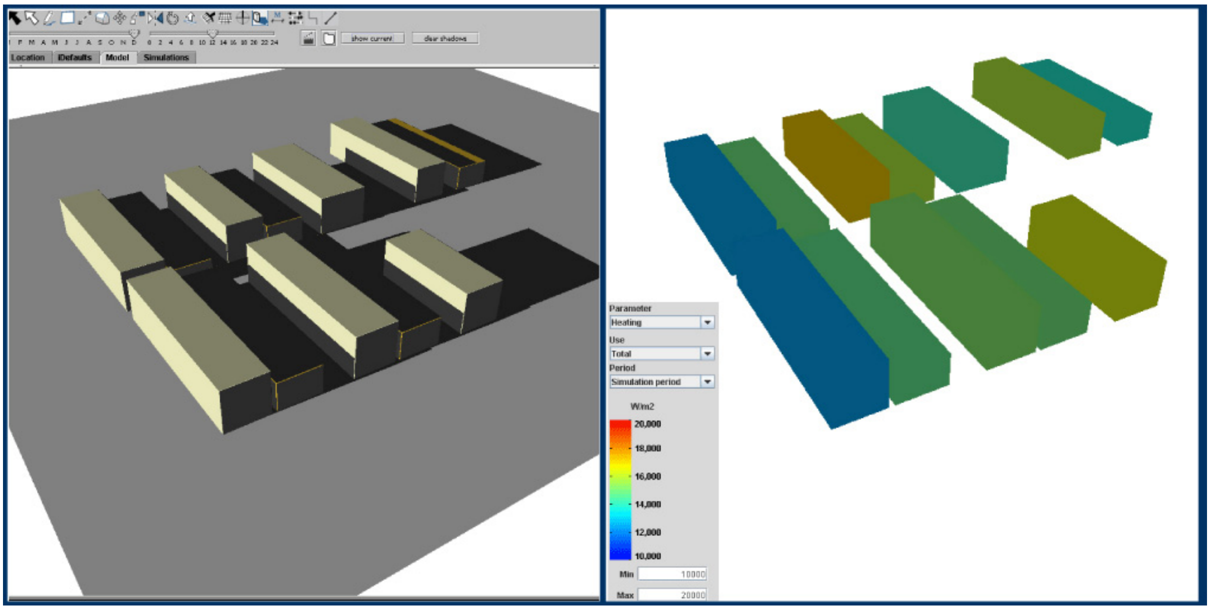


Figure 2.11 SUNtool urban neighbourhood virtual representation (left) with annual heating demand projection (right) (SUNtool 2011)

The ability to redesign the environment, or import new environments representing the possible designs for the neighbourhood enables the stakeholders to investigate a much wider range of "what-if" scenarios; it is not clear, however, if this process can be performed in real time.

ECOTRACT, a CAD based system, has been designed to allow the visual impact of a development to be determined and also the visual analysis of a number of environmental sustainability issues including; resource use (energy and water), solar radiation, shadowing, day lighting and thermal performance (Autodesk 2011; Park & Park 2010). ECOTECT, similar to SUNtool uses a sub modelling approach where the design of the building is used to determine the sustainability indicators and again these are shown to the user using a virtual representation, (Figures 2.12 & 2.13).

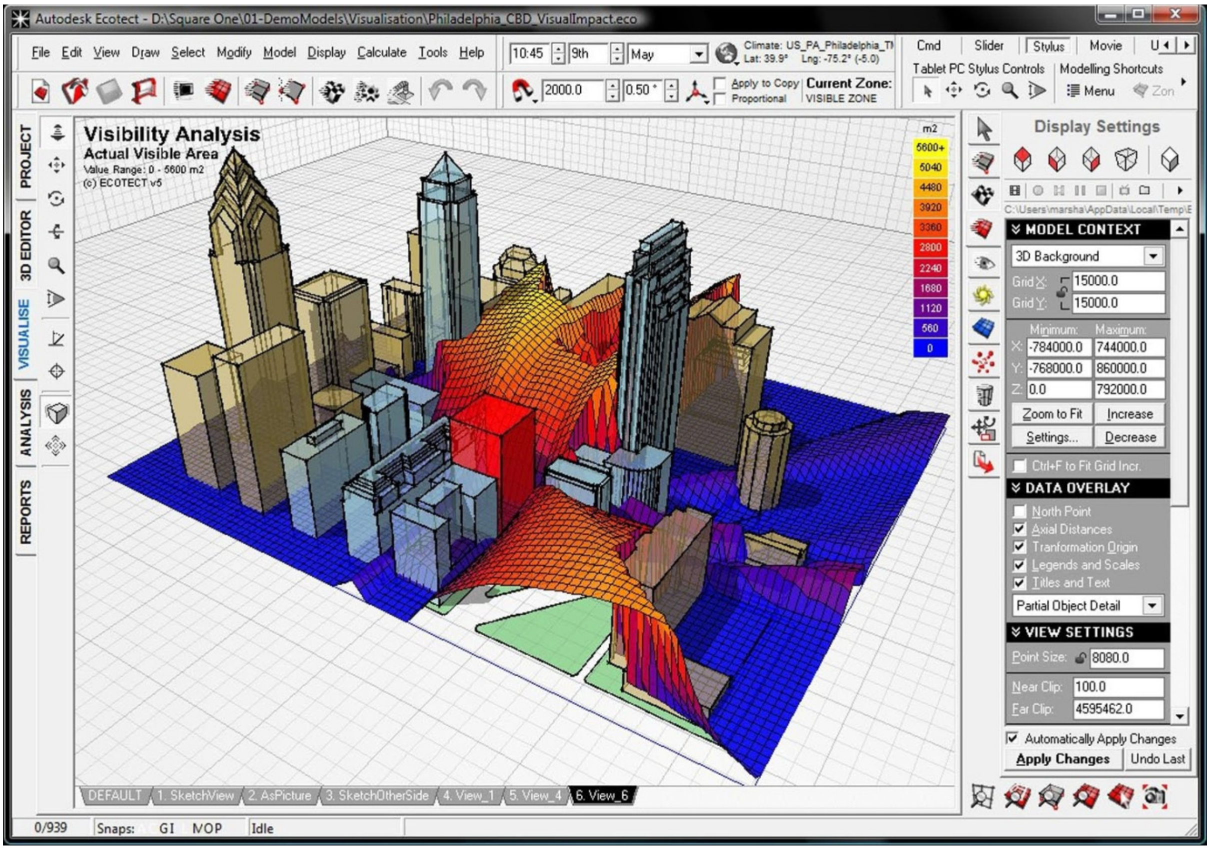


Figure 2.12 Visibility Analysis in ECOTECT(Autodesk 2011)

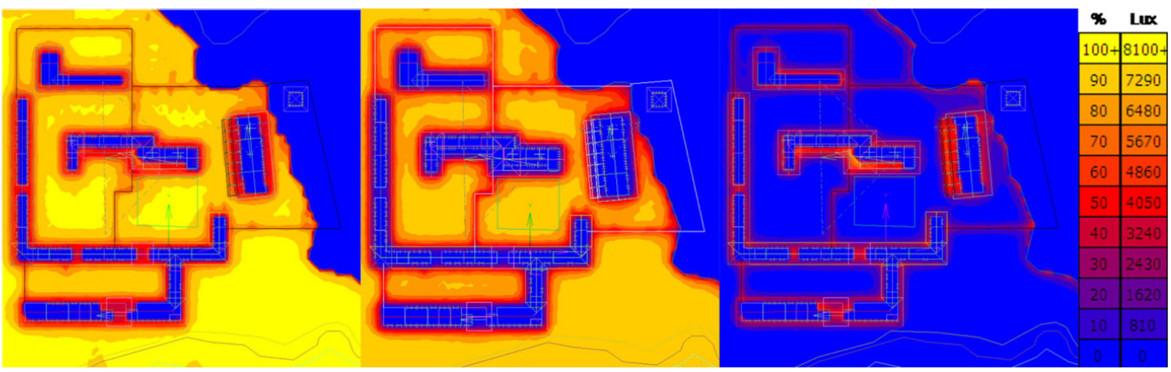


Figure 2.13 Daylight analysis in ECOTECT showing daylight (left) skylighting (centre) and reflected light (right) (Park & Park 2010)

As can be seen in Figure 2.12, ECOTECT does have the ability to include some of the surrounding urban context and this allows for visual representations of some of the covered sustainability aspects. However as can been seen to the right of Figure 2.12, ECOTECT has a complex GUI to provide all the necessary design tools that ECOTECT's target user, the building design expert, requires and is not designed for the novice or non-expert stakeholder or decision maker. Figure 2.13 shows the daylight analysis for a particular building design being studied using ECOTECT, however understanding this analysis and redesigning the building to make improvements would require expert knowledge of building design for daylight (Paranagamage et al. 2010). ECOTECT, being based on CAD software, also suffers some of the problems with CAD based virtual environments discussed in Section 2.3.3.

2.3 Existing Visual Decision Support Tools in Planning and Other Disciplines

Visualisation has been used to aid decision making in a number of fields including increasing the safety and effectiveness of oil drilling in the oil and gas industry (Evans et al. 2002), visualising medical data (Fuchs et al. 1989) and battlefield simulations (Hix et al. 1999).

2.3.1 GIS

Geographical Information Systems (GIS) are currently the most extensively used visualisation platform for decision making. "GIS is now a standard item in planners' tool kits" (Drummond & French 2008) and there are many examples of its use in urban planning and decision making over the last 20 years (Harris & Elmes 1993; Stevens et al. 2007; States 2000; Shiffer 1998; Lodha & Verma 2000). Mainly a GIS system is a graphical user interface capable of entering data to and displaying data from an underlying database system (Kantabutra & Ames 2009). Traditionally GIS provides the user with an interactive data-exploring interface which allows them to overlay a number of different maps onto a 2D surface and allows the user to conduct complex geospatial analysis, such as viewing populations in a neighbourhood, or the boundaries of forests in a landscape (Salter et al. 2009). However it has been shown (Lowe 2004; Lowe 2003) that many non-expert stakeholders have great difficulty in deciphering and understanding scientific displays and maps. Due to its complexity and high learning curve, GIS requires the user "to think like a geographic information scientist" (Clarke 2001) and is still considered to be a difficult to use, expert tool (Traynor & Williams 1995). Its use in decision making has made it difficult for non-expert stakeholders, especially the general public, to participate fully in planning decisions (Salter et al. 2009; Al-Kodmany 2002).

Most GIS systems are strictly 2D, dealing with geospatial data being draped over a map or other geographical representation. While it can be argued that experts can envisage the visual impact of a proposed development from this plan view, it is very difficult for someone not trained in the use of GIS to do this. This can lead to the non-expert stakeholder not fully understanding the consequences of the decisions being made and leave them with an unintended positive or negative view of the planned development (Danahy et al. 1999). 3D representations, however, allow users to quickly recognise the spatial context of the decision and also to orientate their view of the proposed development (Danahy et al. 1999). People develop the ability to navigate and visually process 3D representations of urban environments on a subconscious level throughout their lives as they walk through real world cities (Charters et al. 2002b). This subconscious ability suggests that the user will not have to work to visualise the development, but can concentrate on the decision, and therefore the consequences of the decision, being made. There have been number of different methods of including 3D virtual models in planning decision making.

2.3.2 3D GIS

3D- GIS takes the approach of merging 3D urban models to an existing 2D-GIS. This has the benefit of allowing the GIS user to create a visual representation of the urban environment (Köninger & Bartel 1998). Figure 2.14 shows a 3D layer that has been extruded from a 2D GIS plan.

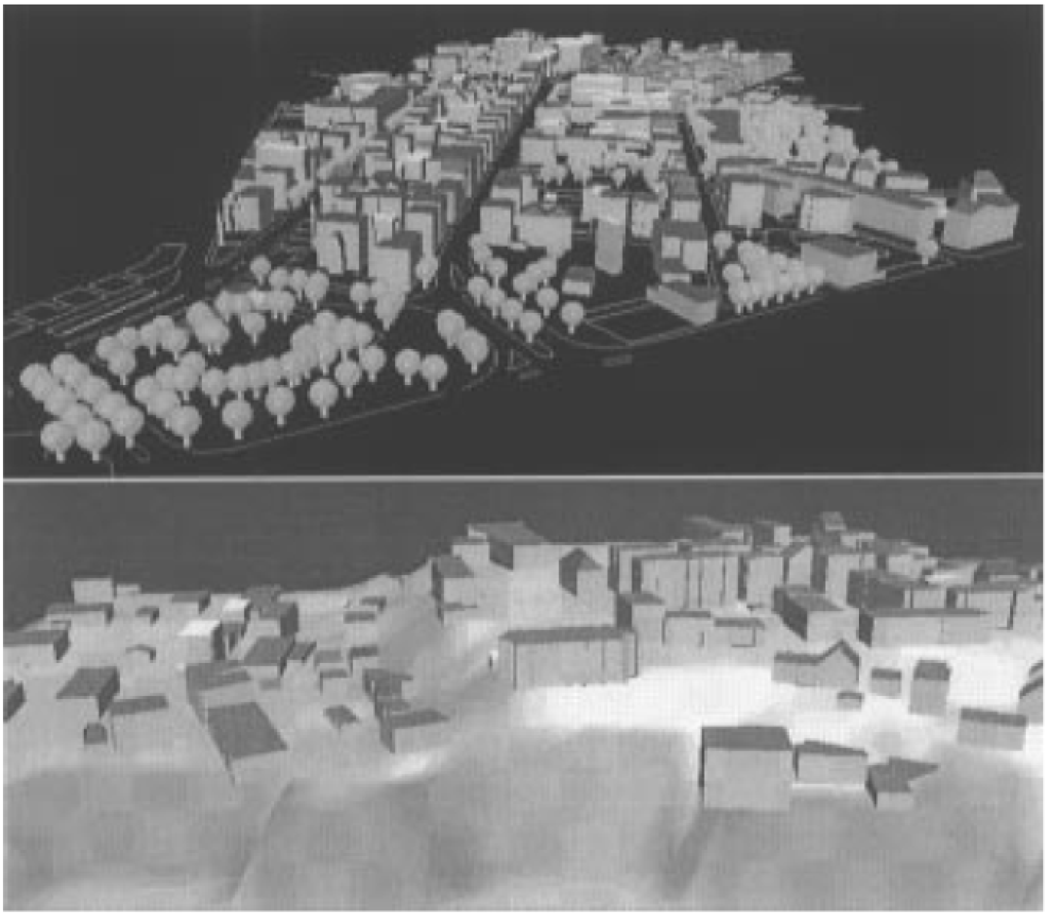


Figure 2.14 A simple 3D extrusion forming a 3D layer in a GIS system.

Ross et al (2009) use a different approach utilising high end graphical and architectural tools to create a 3D virtual environment with which they can overlay specific land use options using vector graphics (images stored as mathematical formulae that will not degrade at increasing zoom levels) (Figure 2.15). Salter et al. (2009) describe the use of the CommunityViz application developed by ARCgis in planning scenarios for new residential developments. CommunityViz acts as an extension to the 2D GIS software and allows for a 3D render of a scenario to be created. In the described example, CommunityViz is used to show 3 predefined scenarios for a residential development; the users can view the appearance of the scenario and then view some of the underlying information, such as water consumption, in graphical form.

Figure 2.15 Vector graphics overlaid on a mix of 3D and 2D representations, showing different land use scenarios (Ross et al, 2009).

Both these examples allow for engaging visualisations, however there are some potential drawbacks. The data contained in existing GIS systems are not designed to reflect a 3D space leading to 3D GIS appearing as if a 3D layer has simply been draped onto a 2D data display, which in effect it has (Hamilton 2005). GIS data is also mainly static, for example if a building's floors are changed this may be reflected in the data view, but its effect on noise pollution for example would not. One main issue with GIS is that it still remains a complex expert orientated tool which is designed primarily to show existing data and, as such, it can appear sluggish due to the large data sets involved; adding a 3D layer only compounds this and would prevent real-time visualisation (Ranzinger & Gleixner 1997).

Extensions to the GIS system which allow for separate 3D visualisation, like CommunityViz above, do attempt to solve this problem by tying the spatial information with the 3D view, however since the GIS content data is continually being changed, the linkage between the geo- spatial data and the VR model library could become invalid after an object has been modified, or deleted, in the GIS (Hamilton 2005).

The planning process undertaken in the design of sustainable urban environments will not only be based on present data, but will have to include past and future data (Harris & Batty 1993). The inclusion of this temporal aspect will ensure that the environments created will still be sustainable in the future. Temporal GIS systems do exist, however these systems do not treat time equally to space and stick to a time-stamping approach, where specific data reflect a single time point, which is inefficient and may leave gaps between time points at different resolutions (Kantabutra & Ames 2009).

Even though many, if not most, planners are now familiar with and use GIS systems extensively (Drummond & French 2008), it has been suggested (Harris & Batty 1993) that GIS does not fully reflect what planners actually do. Namely that GIS is better suited to management rather than making plans. This is reflected in the design of the 3D GIS tools which seem to be better suited to studying a snapshot of data pertaining to a few set scenarios, rather than facilitating the interactive & dynamic creation of multiple scenarios using a "what if" approach. It is clear the latter approach would be most useful for enabling equitable discussion and decisions assessing the most sustainable scenarios.

2.3.3 Virtual environments.

There has also been some previous research involved in developing custom virtual environments for aiding planning decisions. Gaborit & Howard (2004) describe a virtual environment designed to create better public consultation in the design stages of the planning process. The described system uses 3D graphics libraries (open GL) to provide a much more realistic picture of proposed developments than is possible using GIS bases systems and provides some interaction allowing participants to redesign parts of the development. A high level of interactivity in planning is also evident in Heldal (2007) which is designed to support participation in planning new roads. RoadView generates models of road planning scenarios which the user can interact with. Users can, for example, "fly over a road or drive on it (in a car), choose the visibility, speed, and the density of the traffic on the road" (Heldal 2007) to get a feel for how the planned road would look once completed under a range of scenarios.

In the past few years virtual globe technologies like Google Earth (Google 2010) have both become more accessible to general users and more advanced in the functions they can perform (Butler 2006). The GeoGlobe system (Wu et al. 2010) describes how an online virtual globe system can be used to allow the display of a number of possible development scenarios in an urban environment. The system also allows users to add comments about the scenarios which the planners can then review Figure 2.16.

Figure 2.16 GeoGlobe showing 4 different scenarios (this image is combined from 4 separate screen shots).

Ball et al. (2007) describe how 3D visualisation using professional rendering engines of the landscape can allow the public to become involved and gain a better understanding of the placement of wind farms and other land use scenarios in the rural environment. The system described deals with displaying the visual appearance of the scenarios and merging some 2D information on the landscape such as wind speeds or Ordnance Survey maps as shown in Figure 2.17.

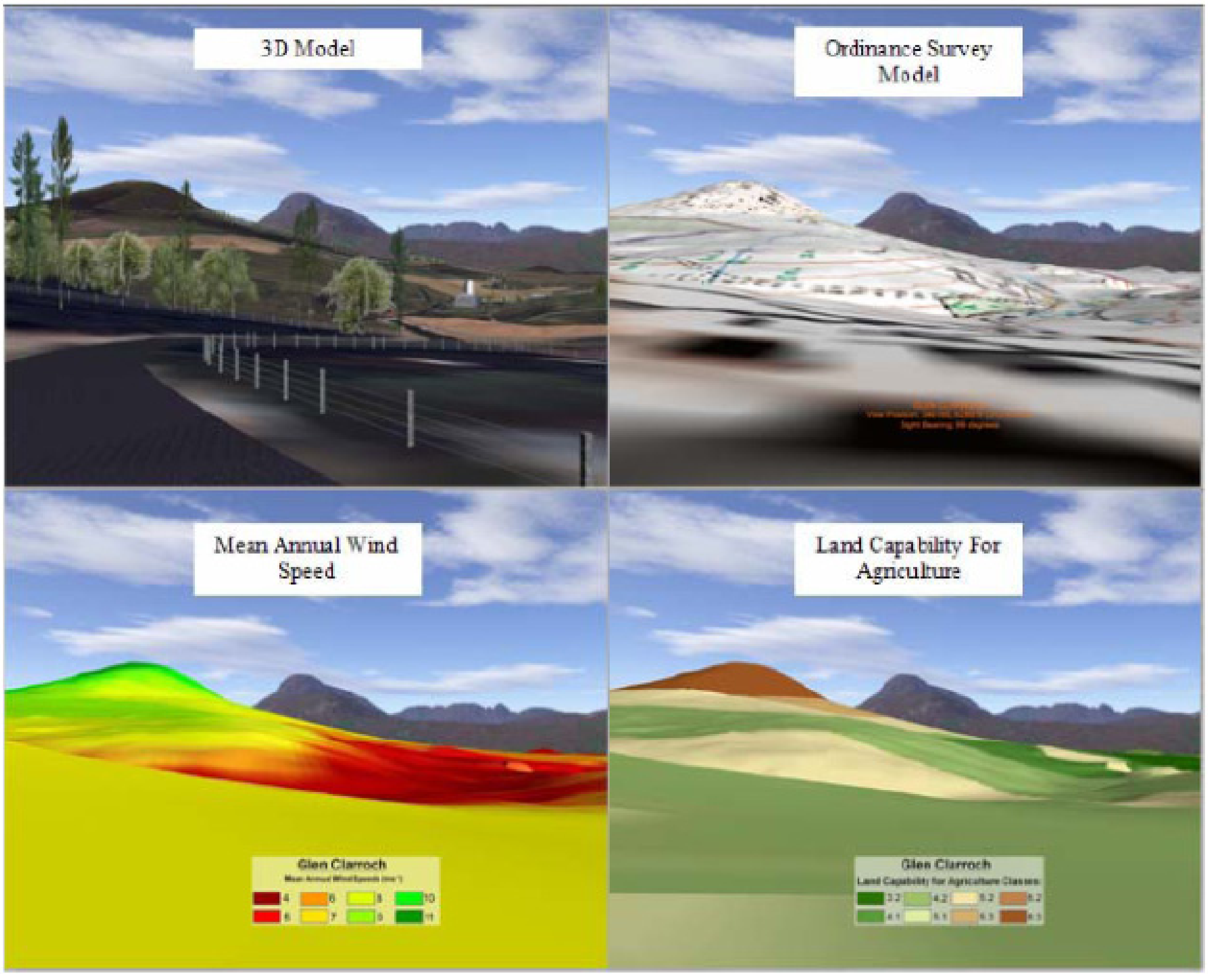


Figure 2.17 Example of layering 2D information on a 3D representation of the environment.

(Ball et al. 2007)

The Macaulay Institute (Miller et al. 2008) has also developed a specialised visualisation system which is designed as an interactive presentation tool for large audiences, with 16 to 20 people viewing at any one time (Figure 2.18). This technique provides a one to many delivery method, where, an instructor guides and controls the experience for all, leaving little room for personalisation. However each member of the audience can vote on the appearance of a particular scenario.

Figure 2.18 Large group participation system (Miller et al. 2008).

Other visualisation systems used in urban planning include CAD based systems and specialised 3D commercial tools such as Autodesk Revit, ArchiCAD and other 3D CAD drafting environments. These products, however, are extremely specialised, requiring very high end hardware due to the levels of realism required by the architectural industry, where these systems are most commonly used. The information visualization and immersive capabilities of these packages are currently limited as they are primarily designed for rendering high quality static images of proposed developments (Drettakis et al. 2007). It has also been suggested that non-interactive or pre-rendered walk- or fly-throughs with a predefined route are not worthwhile in landscape planning (Herwig & Paar 2002). By locking the participant into a predefined route the user may not be able to grasp the characteristics of the scene and the stakeholders become no more than spectators (Danahy 2001; Herwig & Paar 2002)

Combined with this, the fact that these systems concentrate mainly on the physical aspect of the proposed development and were not designed to show underlying spatial or temporal data, means that they lack the ability to effectively visualise sustainability.

2.3.4 Procedural generation modelling and simulation

A major hurdle to the creation of detailed 3D virtual urban environments is the creation of detailed 3D models and their assets (textures, animations etc). This necessitates a time-consuming and expensive content creation process involving the modelling or manual construction of vast amounts of geometric detail: including terrain, roads, buildings, and other associated features (Kelly & McCabe 2007). CityGen employs procedural approaches that will create generic cityscapes. The user is provided with close control over the creation algorithms which control how the roads and buildings within the procedural city are generated (Kelly & McCabe 2007). Procedural city generation is mainly used in games where large urban areas need to be created quickly. Using procedural generation will overcome the problems of creating large areas of urban landscape either by hand or using other technologies such as LIDAR mapping which can be expensive and time consuming. The viability of procedural generation will depend on the urban area being investigated. If, for example, the city to be built was in a completely new and undeveloped space or the developer had free reign to demolish large areas to rebuild on, procedural generation could provide a simple way for stakeholders to experiment with the generation algorithms and view the different possibilities. However, most practical development scenarios will be heavily constrained by the surroundings, including existing buildings which need to remain in place for historical, social or economic reasons and existing or planned connections to existing infrastructure such as roads and utilities.

2.3.5 Colour and 3D visualisation

Colour is a valuable tool in visualisation and has been used in a number of fields to add another dimension to visualisations to increase the amount of data which can be displayed. These techniques have been used, coupled with the display of 3D spatial information in an attempt to display scientific environmental data in more accessible forms. One example, Envision (Bradshaw et al. 2010), uses columns of colour representing the water quality of a number of wells at different positions and depths (Figure 2.19).

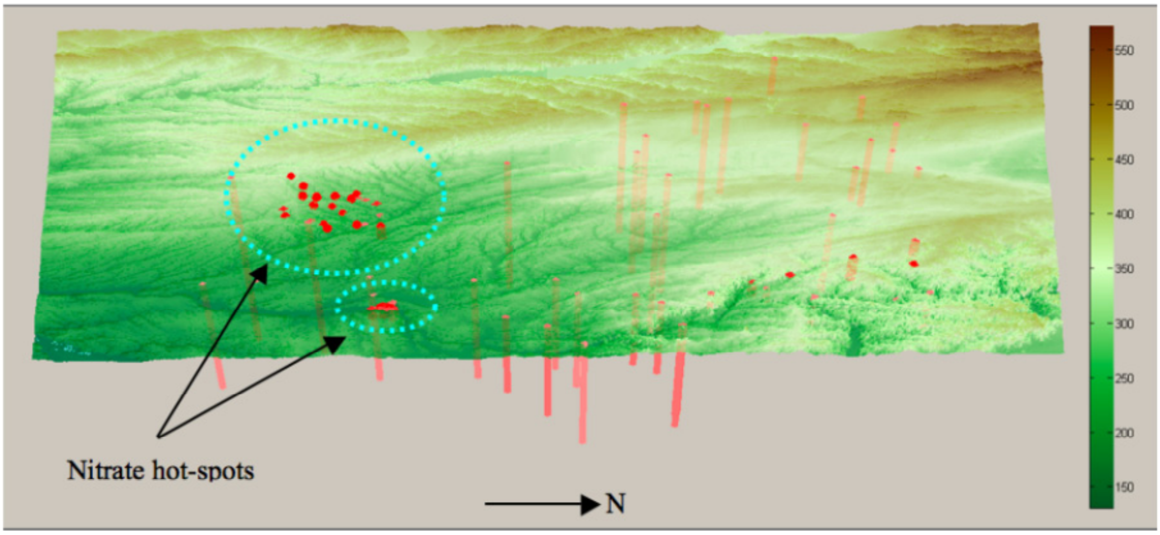


Figure 2.19 The envision system showing contaminant levels in different depth of water well (Bradshaw et al., 2010).

A drawback of Envision is that the datasets are not temporally comparable, with large passages of time passing between the data points that the visualisation is based on. This means that while Envision gives a good method of displaying the available data it would prove difficult to link the visualisation with computational models to predict the effect of possible scenarios on the data. In another example, Nury et al.(2010), use a colour combined with 3D landscape visualisation to investigate ground and surface water flows, again displaying existing data in a new way to aid understanding, as shown in Figure 2.20.

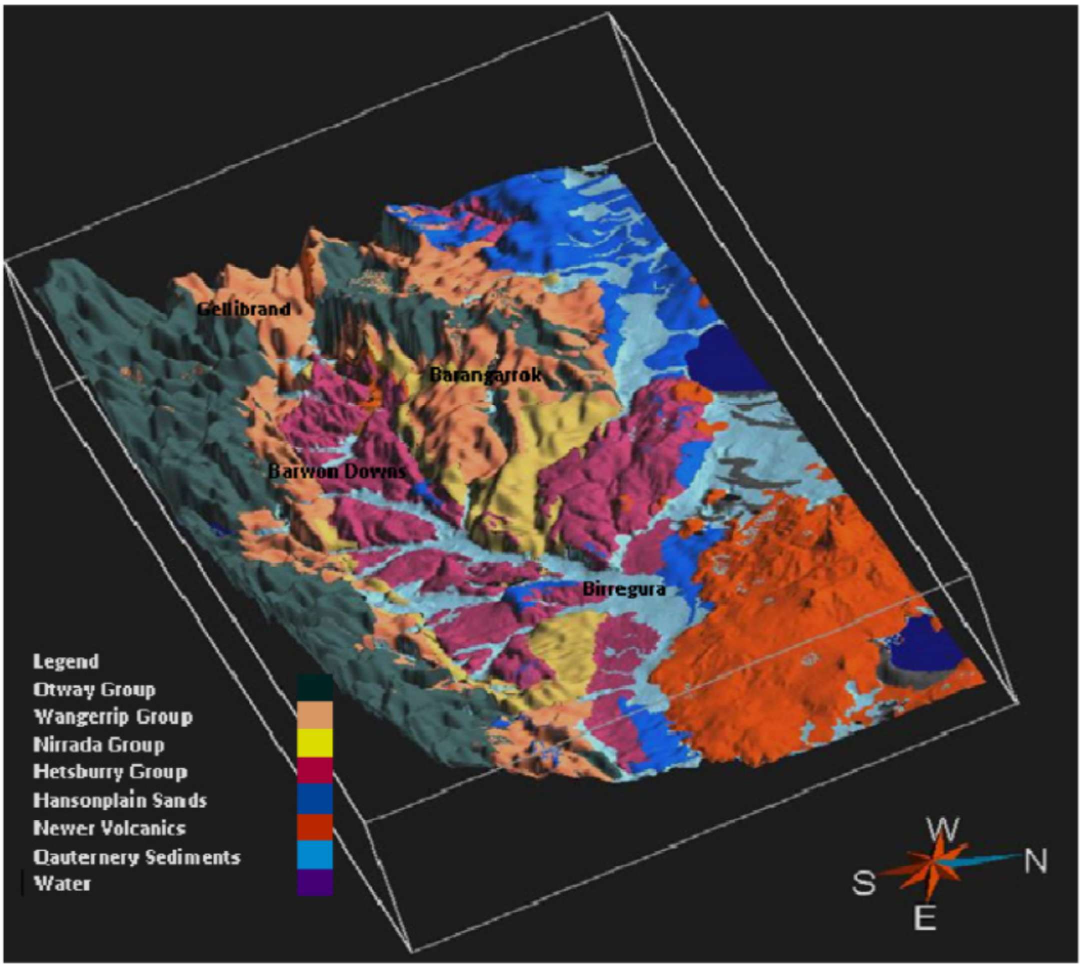


Figure 2.20 Colours used to display rock types for better understanding of underground water flow (Nury et al.,2010),

Hagh-Shenas et al. (2007) have demonstrated that different colour techniques can also be used on a 2D visualisation to increase the amount of data being shown (Figure 2.21).

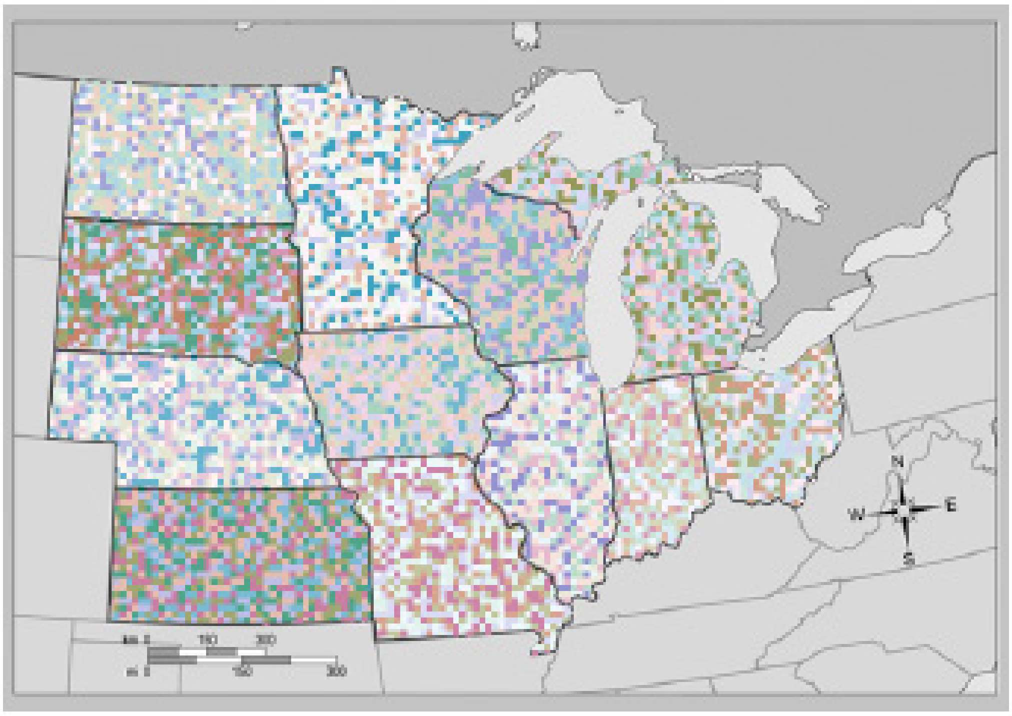


Figure 2.21 2D Weave technique demonstrated by Hagh-Shenas et al. (2007)

It may be possible to combine these colour techniques with 3D visualisation of the urban environment to provide a less abstract view of the underlying sustainability data.

2.3.6 Realism in visualisation

All of the examples above use visualisation in some way but they all vary in how realistic the representation of the environment they produce is. Stanney (2002) suggests that it is not necessarily the aim of a virtual environment to be graphically realistic but that it is realistic enough to engage the user by reflecting the real environment. While photo-realistic graphic realism might not be important, it is, however, important that the physical representations used in the virtual environment fairly represents the real environment (Lange 2005). Also the level of abstraction must not prevent the user understanding what physical entities are being shown. Figure 2.22, for example, shows how a tree could be represented by a single green circle. However it would not be easy for the user to envisage how this tree would look in the environment; is it a young fir or an ancient oak for example, which may impact on whether a user prefers one scenario over another.

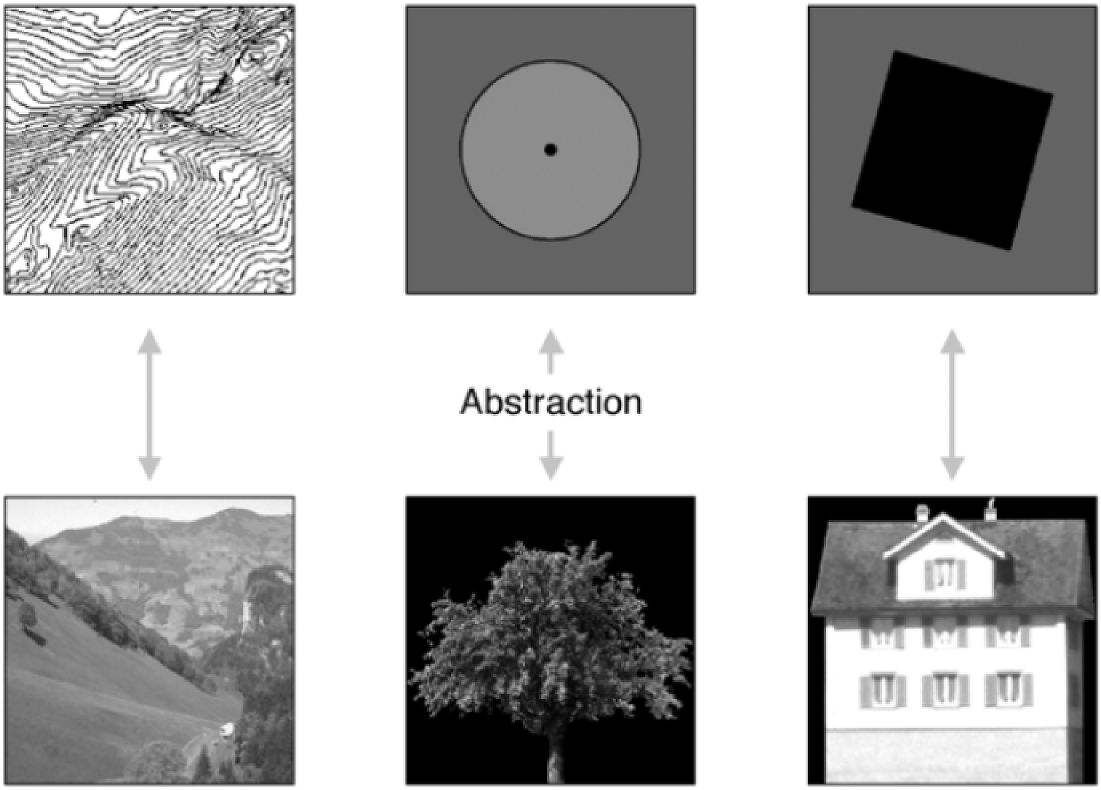


Figure 2.22 Types of abstraction commonly used in planning visualisations (Lange 2005). .

Properties like scale also need to be considered; using a single building to represent a large zone designated for residential purposes may make sense to a planner but may misrepresent the design to a member of the public. It has also been shown, (Appleton 2003), that the level of detail of all the objects may not need to be the same and only the appearance of specific landscape elements, or landmarks, affect how the user will be able to imagine the scene being portrayed.

2.3.7 Games engines and visualisation

Modern computer games are able to provide the user with possible, fantasy or realistic environments with a large degree of interaction, especially over the control of the view or camera with which the user sees the environment. The use of games techniques in 3D visualisation may help the lack of participation and interactivity available in current visualisation methods such as CAD and GIS and may allow for greater realism of the environments being displayed.

Game engines are modular code libraries which handle input, output (3D rendering, 2D drawing, sound), and generic physics/dynamics for game worlds, written for a specific game but general enough to be used for a family of similar games. The ability to separate the code from the function has allowed some researchers to repurpose game code for scientific research (Lewis & Johnson 2002). Game engines are divided into two categories, open source, either old engines or those written by amateurs or closed source, those used to drive current commercial games. OGRE and Irrlicht, are amateur open source "indy" engines which have been used in research projects. The older Doom, Doom2, Quake and Quake2 engines are older commercial engines which have been made open source, however as they are older they lack the more sophisticated rendering capabilities of the newer engines. There are a number of commercial engines which can be used in research projects under academic or student licences which include Torque, Unreal, Quake3 and Half Life 2 (Kot et al. 2005; Herwig & Paar 2002). Older and open source engines will lack some of the features provided by the newer commercial engines which are fully featured and have been extensively designed to support a complete commercial game (Kot et al. 2005). There are a number of examples where games engines have been used in research projects.

Herwig & Paar (2002) have used the Unreal Engine to provide a "stroller's eye" view to aid in landscape visualisation, allowing the user to explore the proposed landscape at will. The project involved the creation of a number of fixed landscape scenarios and allowed the user to navigate and comment on these scenarios. The scenarios or levels were created before the tests in the games level editor, which prevents the user from changing the scenario during the process. The project did however find that the visualisation did seem to engage the stakeholders more fully.

Kot et al. (2005) used the Quake 3 engine to provide the user with a view of abstract data, namely a way of explain programming concepts and source code. In this example the user was provided with a 3D environment in which they could navigate and investigate source code files represented by 3D models on the screen; when the player walks into a object the code is displayed on the screen.

Bishop & Stock (2010) also describe a visualisation system using the Torque game engine to aid in the design of wind farms in Australia (Figure 2.23). The described system allows the user to place the wind turbines and see their effect on the visual appearance of the surrounding environment. The user is also able to experiment with other options like adding trees etc to mask the impact of the wind turbines from differing views. This example is approaching the required level of user interaction that has been suggested in reviews of previous and existing decision support tools for sustainability (Sahota & Jeffrey 2005; Kapelan et al. 2005a) allowing the development of scenarios and the answering of "what–if" questions. The system though is designed for one type of situation (i.e wind farms) and, like many of the other decision support tools that utilise visualisation, concentrates on the physical aspect of the landscape.

Figure 2.23 Wind farm landscape visualisation (Bishop & Stock 2010)

Game engine control & display

One of the principles of ease of use in software applications is the similarity and simplicity of the user interface (Stone 2005). To keep the user interface simple it should use components that the user can recognise as being the same or similar to components they have used before, e.g. user interface controls common on the desktop environment such as labels, buttons, menus etc. This eases the process for the user as they are not required to learn as many new techniques to use the software as they may be already be familiar with their use in other desktop applications (Stone 2005).

Most contemporary computer games, especially those that use high end graphics use "heads up displays" (HUDs) to display information to the user. Each game developer creates a HUD to fit that specific game and although they contain many common elements they are extremely varied from game to game and do not resemble usual desktop applications. Figure 2.24 & Figure 2.25 show two examples HUDs, used in a "first person" game and a "top down" game.

Figure 2.24 HUD in the game Dead Space (EA 2011)

Figure 2.25 HUD in the game SimCity 4(MAXIS 2011)

While it is possible to create custom HUD components which would allow user input, such as buttons, HUDs are primarily for displaying data to the user. The user input for a game usually consists only of movement and interaction controls (fire button etc) through keyboard and mouse buttons and movement which are sufficient for controlling a game. However, for the visualisation tool there will be many more functions which need to be performed such as time control, changing scenarios, environmental effects or visualisation techniques. To use key presses for all of these functions may not be very intuitive and could be extremely difficult to learn and remember.

2.4 Multi Criteria Decision Analysis Models for Sustainability Assessment

Multi-Criteria Decision Making (or multi-criteria decision analysis) is commonly used in decision making problems. Each multi criteria decision will be made up of multiple attributes which represent all the possible aspects which will affect the possible alternative solutions (Triantaphyllou 2000). The approach of MCDA is to treat all of these attributes equally, although weightings may be applied to specific indicators, whether they are monetary or non-monetary, as opposed to economic assessments, or cost benefit analysis which attempt to convert all attributes into monetary terms (Rogers 2001). MCDA approaches attempt to deconstruct the problem by splitting the larger problem into smaller chunks involving each of the individual criteria. It is suggested that by splitting up the problem into smaller parts that the decision maker is able to make a judgement on single criteria that they would not be able to make on the problem as a whole, due to the large amount of information which may need to be considered (Belton & Stewart 2002). As MCDA techniques treat each attribute equally they are particularly suited for sustainable decision making as there is a need in these decisions to include the three aspects of sustainability (social , environmental and economic) and initially treat them as having an equal impact on choosing the most suitable scenario (Rogers 2001).

2.4.1 Multi-Attribute Utility Theory (MAUT)

Traditional utility theory suggests that a decision maker will always choose the option that they expect will give them the most satisfaction or utility. Utility models therefore assume that if a decision maker has two options A and B, that if they expect A will give the most satisfaction, perform the best, they will unquestionably always choose option A (Galotti 2002).

Multi-attribute utility theory (MAUT) extends traditional utility theory by applying it to multi-attribute decisions (Zopounidis & Doumpos 2002). The decision maker must first complete an analysis of the attributes and alternatives. The attributes must be weighted in order of importance, usually on a scale from 0-10. The alternatives must then be given a score to represent their performance against each attribute, again this is usually on a scale from 0 – 10 (Galotti 2002).

MAUT is designed to represent the decision maker's preferences as a utility/value function. This is achieved by applying the expected utility theory to the decision makers weights and attribute scores (Zopounidis & Doumpos 2002).

$$EU(g) = p_1u_1(g_1) + p_2u_2(g_2) + \ldots + p_nu_n(g_n)$$

Equation 2.1 Calculation of expected utility

where EU(g) is the expected utility of alternative g, $u_n(g_n)$ is the utility value (or score) of the alternative g against the attribute n and p_n is the weight assigned to attribute n (Zopounidis & Doumpos 2002).

The application of the MAUT model provides the decision maker with a utility value for each alternative enabling them to pick the alternative which according to their own weightings and scoring will provide them with the greatest satisfaction.

One of the main draw backs of the MAUT method is that it heavily relies on the decision maker's weights and rankings. Many psychologists believe that if the decision maker has not thoroughly thought out the decision before hand and does not sufficiently articulate their values into the model then the weightings and attribute score become meaningless (Galotti 2002).

(Galotti 2002) performed a study on a group of students of differing ability choosing a college in which to study. This study compared the use of the MAUT model, the equal weight model, where all attributes carry an equal weight and the top criterion model where only the attribute with the greatest importance is compared. MAUT did not outperform the equal weight criteria from any group of students, “this suggests that the students aren’t really using the importance weights in coming to a final rating of each alternative”. This trend was also found in further studies of college students choosing a degree course and in pregnant mothers choosing a birth attendant (Galotti 2002).

2.4.2 Simple Multi-Attribute Rating Technique (SMART)

Around 1970 the “engineering psychologist” Ward Edwards began to study the use of MAUT. Although he was enthusiastic about the method he believed that the original version put forward would be too complicated to use in practice and wanted to create a simpler version which would allow its use by a much wider range of people. By 1973 Edwards was leading a research team at the Social Science Research Institute at the University of Southern California. During next decade this team created, over a number iterations, a simplified version of MAUT which would come to be known as SMART (Phillips et al. 2007).

There are eight main steps which must be undertaken to apply the SMART method to a problem;

Stage 1: Identify the decision maker (or makers);

Stage 2: Identify the alternate courses of action;

Stage 3: Identify the attributes which are relevant to the problem;

Stage 4: Measure the performance of each alternative on each attribute;

Stage 5: Determine a weight for each attribute;

Stage 6: For each alternative, take a weighted average of the values assigned to that alternative;

Stage 7: Make a provisional decision;

Stage 8: Perform a sensitivity analysis;

(Goodwin & Wright 1999).

While SMART was designed to be a simpler process, some stages can become more difficult if dealing with a number of decision makers with differing levels of knowledge and experience. The identification of attributes (Stage 3) can be especially difficult if the various decision makers are unsure about the attributes they feel affect the problem. A knowledgeable decision maker may be able to determine attributes at the lowest possible level, whereas a less informed person may be vaguer about what they believe will affect the development. To overcome this problem it is usual for the SMART process to be based on a value tree (Figure 2.26).

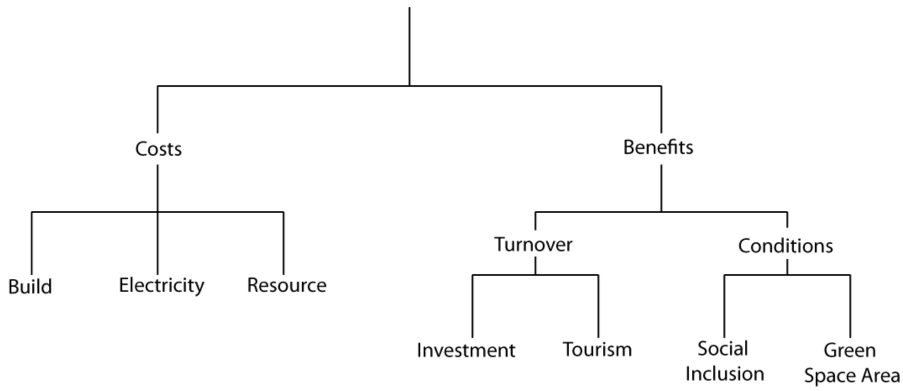


Figure 2.26 Example value tree

During the analysis, the performance of each possible alternative must be measured against the low level attributes identified in the value tree. In most cases the cost attributes will be the simplest to work out as they will be in monetary terms, the decision maker can then produce a total cost for each alternative. Rating the performance of the alternatives becomes more difficult where there is no obvious value with which to compare them. For quantitative attributes, direct rating is used where the decision maker uses his knowledge to rate the alternatives on a scale of 0-100 for a specific attribute. For attributes which have physical values, such as area, but are still determined to be unquantifiable, value functions are used. Value functions allow the estimation of the performance of any alternative between the most and least preferred based on the alternative's physical value (Goodwin & Wright 1999).

SMART requires that the decision maker weight the attributes according to their preference. The weights are calculated by comparing the attributes against each other, again placing each attribute in a scale from 0-100, thus describing the importance of that attribute compared to the others. The weights are usually normalised to make later stages in the analysis easier. The final score for each alternative is then calculated through aggregation of the separate attribute scores. This is usually achieved through the use of the additive model (Goodwin & Wright 1999).

Should money be no object, the decision maker would simply choose the alternative with the highest score. However, if the decision maker is concerned about cost, before a final decision is made the benefit scores of the alternatives must be compared to the costs. This is usually achieved by plotting the benefits against the costs to calculate an efficient frontier. The efficient frontier will contain only the most efficient alternatives, the alternatives which are not dominated by another alternative. This process still leaves the final decision down to the decision maker but that decision can now be more clearly measured in terms of cost and benefit (Goodwin & Wright 1999).

2.4.3 Analytic Hierarchy Process (AHP)

"The Analytic Hierarchy Process (AHP) is a powerful and flexible decision making process to help people set priorities and make the best decision when both qualitative and quantitative aspects of a decision need to be considered" (Expert Choice 2007) .

AHP is designed to simplify a problem by breaking it down into separate parts. It organises the separate elements of the problem into a hierarchy of groupings that will have similar effects on the overall problem. By breaking the problem down in this way AHP utilises the innate human ability to make sound judgements about small problems. AHP analysis allows the decision maker to choose the most appropriate solution, from a number of possible solutions, to a specific problem (Saaty 1990). The steps which must be taken to perform an AHP analysis are outlined below. The data included in the description below is example data to illustrate the process involved.

The decision maker should decide on a hierarchy which suits the problem being investigated. Figure 2.27 shows an example hierarchy for a sustainable development problem.

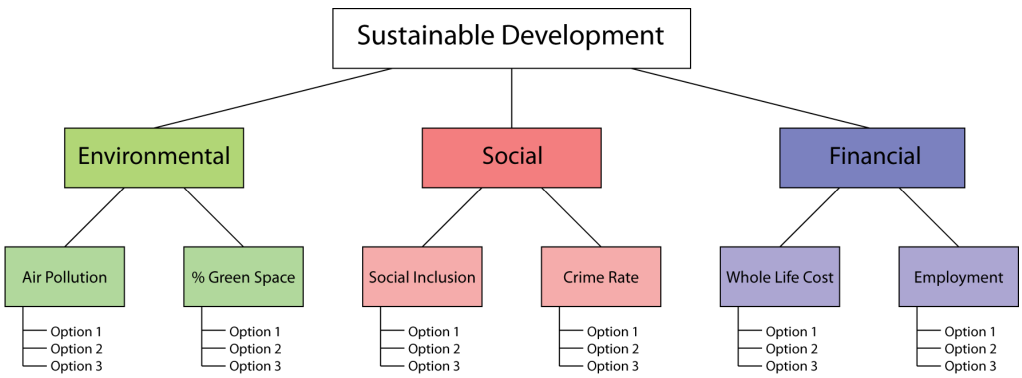


Figure 2.27 Example AHP Hierarchy

The decision maker works down through the hierarchy and using the fundamental scale (Table 2.1) pair-wise comparisons between each element in a group are created.

The pair-wise comparisons describe how important the effect of one element is on another (Saaty 1990).

Table 2.1 Fundamental scale used in AHP (Saaty, 1990).

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
3	Moderate Importance	Experience and judgement slightly favour one activity over another
5	Strong Importance	Experience and judgement strongly favour one activity over another
7	Very strong Importance	An activity is favoured very strongly over another; its dominance is demonstrated in practice
9	Extreme Importance	The evidence favouring one activity over another is of the highest possible order of affirmation.
2,4,6,8	For compromise between the above values	Sometimes one needs to interpolate a compromise judgement numerically because there is no good word to describe it
Reciprocals of above	If activity i has one of the above values assigned to it when compared with activity j, then j has the reciprocal value when compared to i.	A comparison mandated by choosing the smaller element as the unit to estimate the larger one as a multiple of that unit
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining n numerical values to span the matrix
1.1 – 1.9	For tied activities	When elements are close and nearly indistinguishable, moderate is 1.3 and extreme is 1.9

The comparisons identified at each level in the hierarchy can be created as a matrix of comparisons; an example for the sustainable development hierarchy in Figure 2.27 is shown in Figure 2.28.

	E	F	S
Environmental	1	1/2	3/1
Financial	2/1	1	4/1
Social	1/3	1/4	1

Figure 2.28 AHP comparison matrix

When a comparison matrix has been created the elements must be prioritised, which is achieved by calculating the eigenvector, the normalised priority weights of each attribute (Schniederjans 2004). To calculate the eigenvector, each value in the matrix is divided by its corresponding column total. The average of the resultant row totals are then calculated to provide the final eigenvector (Schniederjans 2004).

Calculate column totals

	E	F	S
Environmental	1.000/3.333	0.500/1.75	3.000/8
Financial	2.000/3.333	1.000/1.75	4.000/8
Social	0.333/3.333	0.250/1.75	1.000/8
Column Totals	3.333	1.75	8

=

Calculate row totals						Calculate average		Eigenvector
0.300	+	0.286	+	0.320	=	0.961 /3	=	0.344
0.600	+	0.571	+	0.557	=	1.761 /3	=	0.535
0.100	+	0.143	+	1.223	=	0.368 /3	=	0.121
								1.000

Figure 2.29 Example eigenvector calculation

Calculation of the eigenvector gives the relative ranking of the provided criteria based on the decision maker's original assumptions. In the case of the example shown in Figure 2.29, it can be seen that the financial aspect has the greatest effect followed by the environmental and then the social aspects. This process is completed for each level of the problem hierarchy (Schniederjans 2004) (Figure 2.30) .

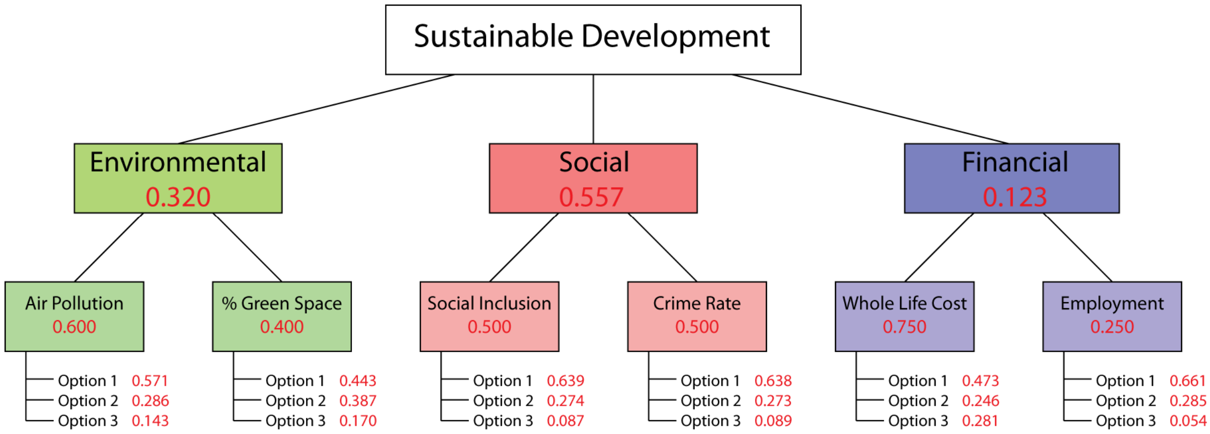


Figure 2.30 Completed prioritised hierarchy.

For each of the lowest levels of the hierarchy, each possible alternative is compared against the others for that element. This results in a comparison matrix and therefore and eigenvector for each of the possible solutions. The final evaluation can be performed by aggregating the weights at each stage for each option (Figure 2.31), in this case Option 1 is the most appropriate based on the decision maker's initial priorities (Forman and Gass 2001).

Figure 2.31 Aggregation of priority weights

AHP allows the decision maker to gain a better understanding of the problem by breaking it down into a structure which shows the problem's key elements and the relationships between them. The hierarchy formed creates a simple start to finish framework providing the decision maker with a distinct path to follow. The decision maker can include their own personal knowledge, feelings and emotions at each stage in the assessment, which helps to make them feel more a part of the final decision than if it were simply a numerical measure. Above all the process gives the user a clear numerical indication about which of the provided alternatives is the 'best' (Saaty 1990).

However a number of weaknesses with the analytic hierarchy process have been identified. The comparison method used in AHP allows for the occurrence of inconsistent transitivity relationships. While using single criteria it would be unlikely that an intransitive relationship would occur; when dealing with multi-criteria problems it is much more likely that intransitivity will occur. This is because the "decision maker cannot simplify the complexities of the problem to achieve true transitivity" (Forman & Gass 2001). The following example shows the type of decision where intransitivity can occur;

"Professor P is about to change jobs. She knows that if two offers are far apart on salary, the salary will be the determining factor in her choice. Otherwise, factors such as prestige of the university will come into play. She eventually receives three offers, described below.

Option	Salary	Prestige
X	$65,000	Low
Y	$50,000	High
Z	$58,000	Medium

Professor P concludes that she prefers X over Y, Y over Z and Z over X. This leads to an inconsistent transitivity relationship between the options (Fishburn 1991).

AHP also allows for rank reversal to occur. Rank reversal is a change in the result of an AHP analysis due to the addition of an extra option. Rank reversal occurs because

AHP is based on a 'closed system architecture' where the result is based on a fixed number of choices; when an extra choice is added it changes the mathematical result wherever it appears in the final rankings (Forman & Gass 2001).

Example of rank reversal;

Two options A and B are evaluated according to two equally important attributes X and Y giving the following matrices.

Option A & B for Criteria X

	A	B	Eigenvector
A	1	5	0.83
B	1/5	1	0.17

Option A & B for Criteria Y

	A	B	Eigenvector
A	1	1/3	0.25
B	3	1	0.75

The priorities obtained for A and B are 0.542 and 0.458 respectively, therefore A is preferred to B.

A third option C is then introduced and compared with A and B.

Option A & B & C for Criteria X

	A	B	C	Eigenvector
A	1	5	1	0.455
B	1/5	1	1/5	0.090
C	1	5	1	0.455

Option A & B & C for Criteria Y

	A	B	C	Eigenvector
A	1	1/3	2	0.222
B	3	1	6	0.666
C	1/2	1/6	1	0.111

The priorities are now 0.338 for A, 0.379 for B and 0.283 for C. This results in B now being the preferred option a rank reversal from the comparison of A and B (Saaty 1990).

AHP analysis is often used in choice decisions. This is where one option is to be selected from a set of possible alternative options. Possible choice decisions include product selection, vendor selection and policy decisions (Forman & Gass 2001). AHP can also be used to determine the relative benefit of a set of possible alternative options. In this case the difference between the eigenvector values and the order of priority are as important to the decision maker as finding the option with the highest priority. Prioritisation can be used in the selection of a combination of possible alternatives (Forman & Gass 2001). Resource allocation is another area in which AHP can be useful. There will be multiple objectives, perspectives and resource allocation alternatives which can be rated according to their relative effectiveness toward the organisation's/decision maker's goals (Forman & Gass 2001). AHP can also be used in benchmarking procedures. For example, a company can compare one of its procedures or products with those of other companies to ascertain which company is the 'best' in a specific area or overall (Forman & Gass 2001). AHP allows the modelling of both qualitative and quantitative data. Qualitative data representing the user's views is entered using the pair wise comparison detailed above. Quantitative data can be modelled by applying synthesised eigenvectors created through normalisation of data from the possible scenarios.

2.4.4 Analytic Network Process (ANP)

The analytic network process (ANP) is a more advanced framework based on the same mathematical principals as the analytic hierarchy process (Decision Lens 2007). In AHP a goal-orientated hierarchy is created in which the components of the problem are arranged in levels of descending order of importance or influence. The ANP method uses interactive network structures which give a more holistic representation of the overall problem (Saaty 2006).

As opposed to the AHP method the, ANP method does not connect elements in any specific order. Instead the components of the problem are connected, as appropriate, in pairs with directed lines. Instead of a hierarchy, components are connected via an arrow which simulates the influence of one component over another. The components in a network may also be regarded as elements that interact and influence each other in regard to a specific attribute. “That attribute itself must be of a higher order of complexity than the components” (Saaty 2006) and is called a control criterion. The use of control criteria means that ANP also displays a form of hierarchical structure which lists control criteria above the network.

To perform a ANP analysis the decision maker must identify the network through analysis of the problem to be solved. The decision maker must identify the clusters, elements and the relationships and interactions between them (Bottero et al. 2007). An example network for a sustainable development scenario is shown in Figure 2.32.

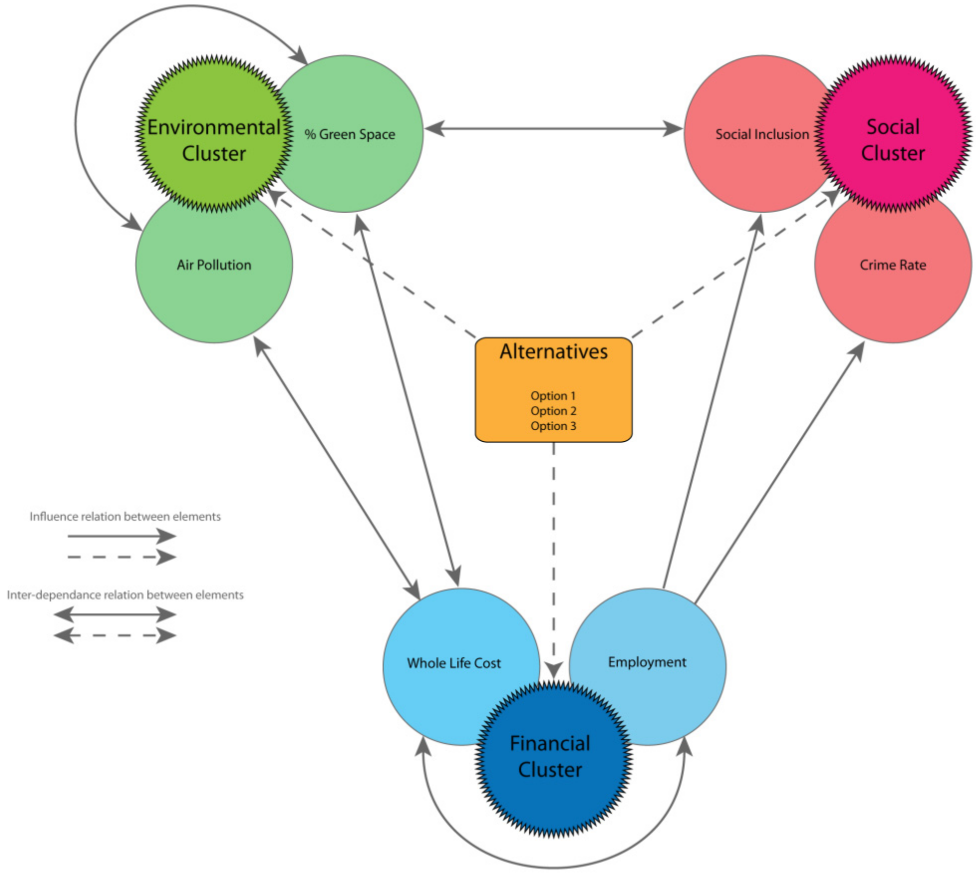


Figure 2.32 Example sustainable development network model.

Once the decision maker has constructed the network to be analysed they must now create a supermatrix describing the interactions defined in the model (Gencer & Gurpinar 2007). The supermatrix is created using the fundamental scale and pair-wise method used in AHP, however every interaction is described in terms of every element it interacts with (Saaty 1999).

Table 2.2 Example supermatrix structure used in ANP analysis

	Alternatives			Environmental		Social		Financial	
	Option 1	Option 2	Option 3	Green Space	Air Pollution	Social Inclusion	Crime Rate	Life Cost	Employment
Option1									
Option2	0			W1		W2		W3	
Option3									
%GS	W4			W5		W6		W7	
AP									
SI	W8			W9		0		W10	
CR									
WLC	W11			W12		0		W13	
E									

Table 2.2 shows the supermatrix structure for the network outlined in Figure 2.32. The cells W1-W13 would be filled with eigenvectors calculated from the comparison matrices for that element. Those cells that contain zeros show that there is no interaction between these two clusters (Saaty 1999).

The supermatrix that is created is via this process is known as the initial or un-weighted supermatrix as it does not yet express the weightings of the overall clusters (Saaty 1999; Saaty & Vargas 2006) . A pair-wise comparison matrix must be created to represent the relationship between the clusters, in this case environmental, financial and social. Once this has been completed the calculated eigenvector is applied to the un-weighted supermatrix, this results in a final weighted supermatrix. The eigenvector calculated from the weighted matrix will give the decision maker the prioritised list of elements.

ANP allows for the modelling of much more complex problems than AHP (Saaty 2006). By allowing cross-cluster interactions as well as inter-relationships between elements, ANP is structured more naturally than AHP and allows for a more realistic representation of the problem. The analytic network process still provides the user with the ability to include their own personal knowledge and feelings about an interaction through the use of pair-wise comparisons (Saaty & Vargas 2006; Bottero et al. 2007).

While ANP is structured more realistically than AHP, it does not provide the user with as simple a view of the problem (Saaty 2006). It could be argued that the user would identify more easily with the simplistic hierarchy provided by an AHP assessment. While ANP can model more complex problems, it is a much more complex process and would not be as easy to learn to use. This is in conflict with two of the descriptions of what a decision making system should be put forward by AHP and ANP's creator Dr Thomas Saaty. Namely that a decision making approach should be "simple in construct" and "not require inordinate specialization to master and communicate" (Saaty 1990).

The analytical network process can be applied to similar problems as the analytic hierarchy process, however it can handle more complex problems. Also, linear models can only predict forward, so the non-linear ANP method is beneficial for problems where the consequences or effects of the alternatives is needed (Saaty 1999). Currently ANP is mainly used in the business sector for measuring market shares for a specific business type (Saaty 2006) Like its predecessor ANP, AHP can model a mix of quantitative data from the possible scenarios and qualitative data based on a particular users view and experience.

2.5 Summary of Literature

It is clear from the review of the sustainability literature that sustainability and its assessment in the urban environment is a complex issue. This complexity derives from the fact that any assessment must draw criteria from the three aspects of sustainability (Sahota & Jeffrey 2005) to ensure that our future cities or developments provide more effective and efficient services, maintain public health and welfare and reduce harmful resource usage (Foxon et al. 2002). It is also clear that this process is made even more difficult by the need to include a diverse range of stakeholders in the decision making process when these new developments are planned. To be effective, the decision making process is dependent on all the stakeholders involved being genuinely involved in the whole decision making process, but the current prevailing practice is for decision makers to seek agreement for proposals once the key decisions have been made (Geldof 2005). For an urban environment to be truly sustainable all people of need, interest, experience and geographical proximity to a development should be involved in its creation and maintenance (Charnley & Engelbert 2005). In particular it has been shown that engagement with the general public throughout the decision making process presents a number of major challenges. These include not only communicating the complexity of sustainability in general and its implication to the decision making process but also in providing an understanding to stakeholders of the short and long term implications of alternative courses of action (Beierle & Cayford 2002).

Sustainable decision support tools have been developed but a major barrier to the development and implementation of tools to support urban design is the complexity of the environment in which decision are made(Bouchart et al. 2002; Ashley et al. 2004; Hull & Tricker 2005). It has also been shown (Kapelan et al. 2005; Al-Kodmany 2002) that these tools lack the ability to engage all the stakeholders due to their focus on "expert" decision makers (e.g. planners, architects, and design engineers).

Kapelan et al. (2005) suggest that 3D visualisation will be the key to new decision support tools which will enable a wider participation of stakeholder by enabling more effective communication between experts and non experts. This view that visualisation aids stakeholder involvement in the decision making process has been reinforced by a number of other studies (Ball et al. 2007; Miller et al. 2008b; Hamilton 2005; Hamilton et al. 2001; Salter et al. 2009; Gill et al. 2010; Wu et al. 2010; Bishop & Stock 2010) where visualisation has been used in public consultation for a variety of planning decisions. However, all of these examples concentrate on the physical appearance of the decision being made and were not designed to confer any information to the stakeholders. Those examples which use GIS combined with 3D component to show some of the underlying information suffer the same issues as the original 2D GIS systems, i.e. they are expert orientated, static systems (Drettakis et al. 2007; Harris & Batty 1993). Furthermore none of these system deal specifically with sustainability; like many of the decision support tools that do not include visualisation, 2D or 3D, these tools only deal with a specific problem (e.g. wind farms) or aspect (e.g. environmental). It is also extremely difficult to determine whether any of these systems have actually led to a change in policy, or a different decision being made.

One important aspect of sustainable indicators is that they will change over time as highlighted in Hanley et al. (1999). This is especially important in urban developments, as if the values of the indicators on which the sustainability of the development is based are constantly changing, the overall sustainability of the development will also change. While a development may be sustainable over a long period of time, e.g. the life time of the project, it may be unsustainable during certain phases such as construction where for example no money will yet be being made and high levels of noise pollution will be present. It is important that S-City VT is able to model the indicators over time to ensure these changes are effectively highlighted to those stakeholders that may not have a full understanding of sustainability. To make the process fully engaging the user should be able to make changes to the indicators in real time developing "what-if" situations, a process which does not seem possible using current systems.

Appleton (2003), Lange (2005), and Davies & Laing (2002) have all shown that the realism of any visualisation of the real world is important in engaging the stakeholders. Lange (2005) in particular shows that the representation of the real world must be fair to the stakeholders and any visualisation should not, either intentionally or unintentionally, mislead the users or influence their choice of scenario through the use of a particular abstraction or visualisation technique.

As has already been stated, many of the existing decision support tools do not adequately reflect the sustainability decisions being made as they do not include all the aspects of sustainability. To effectively model all aspects of sustainability it will be necessary to include some form of multi-criteria decision analysis (MCDA) technique which will reflect how the sustainability indicators interact. It is the aim of the MCDA techniques to make decisions based on a number of criteria more explicit, rational and efficient (Hobbs & Meier 2000). The use of a MCDA technique will allow for the creation of a single indicator, which may help the stakeholder identify more sustainable scenarios by reducing the complexity of the choice being made. Many MCDA methods can be perceived as "black box" tools if the decision maker does not understand how the method actually works (Loken 2007). As it is important that any new decision support tool engages a wide variety of stakeholders it is important that the MCDA technique used is as transparent as possible but also reflects the how the stakeholders actually feel about the scenarios on which the decision is being based.

MAUT, SMART, AHP and ANP all seem to provide MCDA methods which will simplify the decision being made but the weights of which will also remain transparent to the user. MAUT will allow for the wide range of criteria required for sustainable decision making, however it strongly relies on the stakeholder applying a utility value to each criteria which can be very difficult if the stakeholder is not sure of their risk preferences (Loken 2007; Galotti 2002; Siskos & Hubert 1983). This issue is highlighted in the studies undertaken by Galotti (2002) where a MAUT analysis did not differ significantly from an analysis performed using an equal weighting.

SMART also relies heavily on the decision maker being able to rate the benefit of each criteria; these benefit scores for each scenario are then compared with the cost of that scenario (Goodwin & Wright 1999). A SMART analysis performed in this way does not seem to adequately reflect the principle of sustainability where the economic cost should be an integral part of the analysis which can be affected by other criteria, not just a means of identifying the cheapest solution.

AHP and ANP have both been identified as simple, flexible, intuitive and able to handle both quantitative and qualitative criteria in the same framework (Ramanathan & Ganesh 1995). AHP and ANP also provide the ability to integrate the large number of criteria involved in the sustainable decision making process. Both processes suffer some drawbacks in that they are time consuming in defining the networks involved. However as ANP and AHP provide the user with the ability to include their own personal knowledge and feelings about an interaction through the use of pair-wise comparisons (Saaty & Vargas 2006; Bottero et al. 2007), these methods do seem to provide a very transparent process. As has been shown sustainability is not linear, the three aspects do not exist in isolation, but are inherently linked (Sahota & Jeffrey 2005; Foxon et al. 2002); the hierarchical nature of AHP does not adequately fit the decisions being made. ANP, however, allows for interactions between all criteria to be described (Saaty 1999), thus reflecting the interactions between all the indicators which need to be considered in decision making for sustainable environments.

Existing 3D engines, such as those used in contemporary computer games are not designed to show the kinds of information which is required by the sustainability models. Further many existing 3D engines are commercially based and owned by large development companies, meaning that their use is extremely controlled through the use of expensive licences even for academic products. This commercial bias also entails that the development of the sustainability models and scenario design would need to be developed around the capabilities of any existing 3D engine chosen, which may limit the flexibility of the final application as a commercial company would be unlikely to add desired additional functionality to their product. Some games engines do provide less expensive "Indy" licences such as the Torque game engine (TGE) and there are some free 3D engines such as IrrLicht, however both these solutions still rely on previously written code which was not designed for the specific purpose of displaying sustainability in 3D environments and, as has been discussed in regard to 3D GIS, taking the approach of "bolting on" features many not lead to successful results.

As can be determined from the review of the existing sustainability decision support tools, there is no single tool that includes all the components above which have been argued as being important in the decision making process. It is clear then that there is the need for the creation of a new DST that combines the best features of the existing

DSTs and 3D visualisation to provide a more holistic approach to decision making in the planning of sustainable urban environments, which includes sustainability modelling and visualisation.

2.5.1 Requirements for S-City VT;

SCity VT will be required to provide a detailed impact assessment of proposed action and developments and will provide information about the possible tradeoffs between the sustainability pillars. This allows stakeholders and decision makers for the development being modelled to determine the social, economical and environmental impacts of decisions they make before the real development is created. Towards this the sustainability DST (S-City VT) will uniquely combine sustainability modelling (encapsulating sustainability indicator modelling and sustainability assessment) scenario design and visualisation techniques (Figure 2.33).

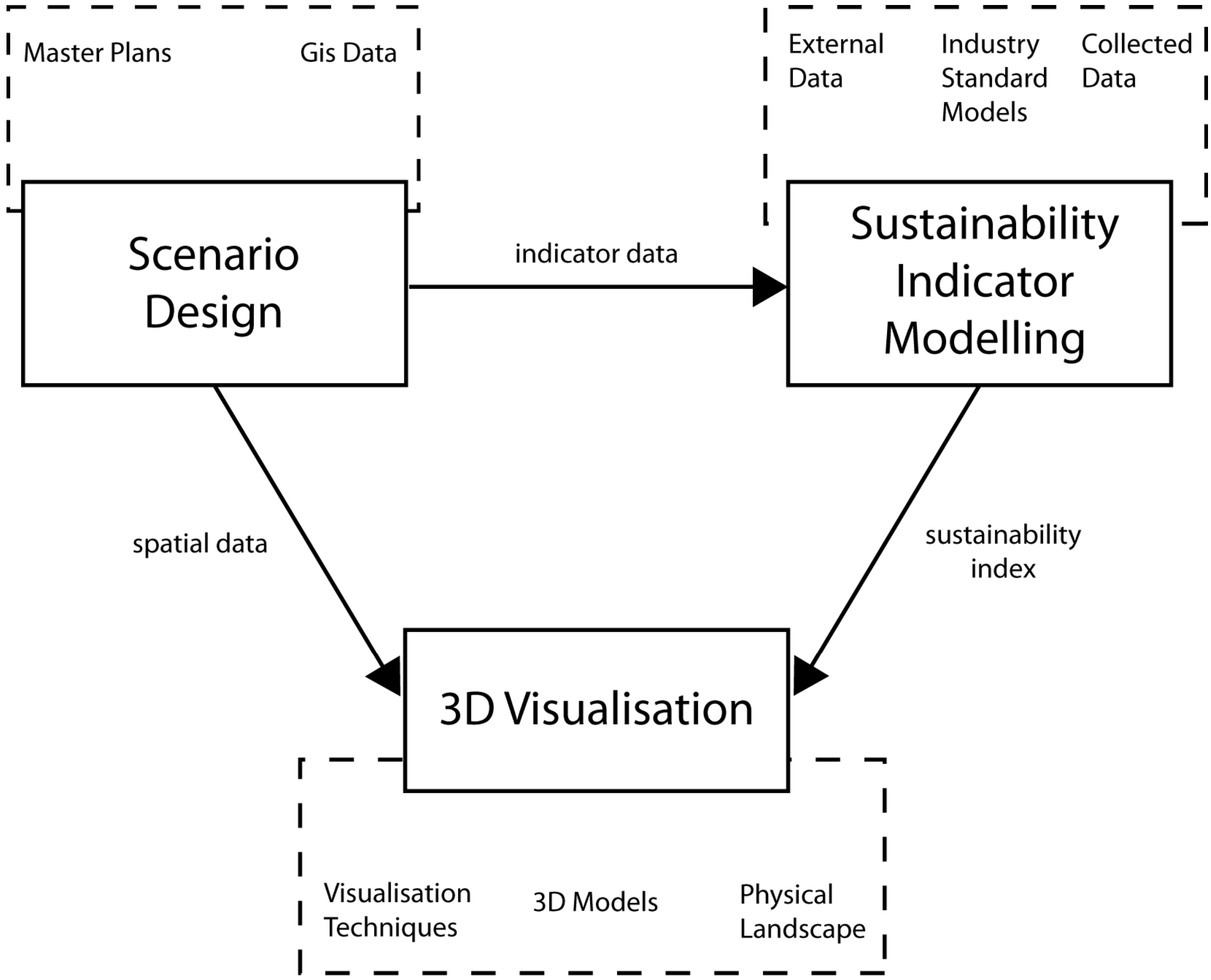


Figure 2.33 Components of the S-City VT decision support tool

Sustainability Indicator Modelling with Multi-Criteria Sustainability Assessment

Models will be developed to describe how each indicator changes due to spatial and temporal conditions. Through the use of ANP the sustainability assessment can be presented to the user as an aggregated value, giving a single indicator of sustainability. Should an expert stakeholder not wish to only be presented with a single indicator, it will also be possible to see the separate indicator values. Where possible the DST uses indicator values and other data used will be derived from real world data either collected or sourced from existing databases or modelled by existing industry standard models. Sustainability indictor modelling and multi-criteria sustainability assessment are covered in more detail in Chapter 4 & Chapter 5 respectively.

Scenario Designer

The scenario designer should allow the user to create and design their own scenarios, this would entail not only changing the data involved in the scenario, that will affect sustainability, but also changing fundamental options such as the buildings position in the development or different building proposals. Some generic scenarios should be built into the model; it is also important that the user be able to add their own custom scenarios, as it is unknown now what new scenarios could happen to affect developments in the future. The government or local council could also change policy on any number of issues throughout the lifetime of a development, a city wide recycling policy for example. The model must be able to cope with any effects these policies could have on a development. As it is unknown what the government could decide to do in the future so again the user must be able to supply their own policies which can be incorporated into the model. The scenario designer must also incorporate temporal factors to allow the user to determine how decisions made at different stages in the life of the development would combine to impact on the sustainability of the development. The development and operation of the scenario design component of S-City VT is covered in Chapter 6

3D Visualisation

The tool will utilise 3D/virtual reality visualization techniques which will form the interface between the complex model and the data being manipulated and modelled. As this is the case, the visualisation aspect of the tools implementation will determine the success of its use. It is envisaged that the tool will include a 3D view of the area of development. This 3D view will be used to show the information provided from the model component of the system. By using a 3D system in this way, a stakeholder will not only be able to determine the effects of decisions made but also be able to view them in a real-life context. The visualisation component should provide the user with the opportunity to see how their decisions and scenarios affect the sustainability of the wider area; a single decision will not only affect a single building or road but will have an impact of the development as a whole. As with the scenario designer, the visualisation component of the tool should include a temporal aspect to allow decisions enacted at different stages to be visualised. With this in mind, the interface should provide the user with the possibility of selecting different spatial and temporal scales in which the impacts of the decision can be seen. The development of the visualisation component is detailed in Chapter 7

The complex functionality being developed will be of no use to the stakeholders if they are unable to access and understand how to use it. It is extremely important that the visualisation component contains a simple but effective graphical user interface which will allow people not familiar with the system to be able to use it and to gain a valid, meaningful result. Chapter 8 details the operation of the visualisation techniques used in S-City VT.

Chapter 3 Case Study

Chapter 2 developed a set of requirements which a new decision support tool should have. The development and testing of the tool will require the identification of one or more urban development projects where sustainability assessment was required. There were three possible strategies for this stage of the work. One strategy would involve data collection from a number of real developments which would give rise to a large volume of processes and data on which the development of the application could be based. However, there were two major drawbacks to this approach, namely:

- It would rely heavily on finding cities or urban environments where developments were taking place with comparable time and spatial scales. This could prove difficult as developments of sufficient scale to require sustainability assessment usually have long time scales (10 – 30 or more years) and due to their capital cost it is unlikely that there will be a large number of developments occurring concurrently.
- The nature of sustainability assessment entails that one development may be sustainable in one area or city and not in another. This will mean that the indicators collected across a large number of developments will not necessarily be the same as the importance of these indicators may vary from development to development.

The second strategy would have been to develop a fictional exemplar city which would attempt to reproduce some of the aspects of a real urban environment. This was not deemed suitable because:

- As already stated effective decision making relies on the engagement of all the decision makers. A fictional city may be too abstract for the stakeholders to fully engage with. As a stakeholder, by definition, is someone who has a stake in the decision being made, it could be argued that in a fictional development no one really has a true stake.

- The sustainability issues created for a fictional city could become contrived or be based on too many assumptions about the issues. This would clearly not only affect data and how the indicators are modelled by the DST but could also affect how the tool is perceived by the experts.

The third strategy was to adopt a case study approach to select one real development to apply the tool to; this was deemed to be appropriate because:

- The case study provides an opportunity for intensive analysis of a single instance of the topic of study (Swanborn 2010). In this case one development could be concentrated upon to allow the sustainability of the development and its options to be fully reflected by the DST.

- A development could be selected where it is known what the important issues are and what indicators are already measured allowing the participating organisation to become more easily involved.

- A real development will have real stakeholders, which allows the research to be based on participants who will be already interested in the development and may wish to be engaged in the decision making process.

The following section provides a description of the case study development chosen and the reasons for this choice.

3.1 Dundee Water Front

The city of Dundee is located on the north bank of the river Tay Estuary on the east coast of Scotland as shown in Figure 3.1. The following sections describe how Dundee, and its waterfront, developed into the city as it is today.

Figure 3.1 Location of Dundee within western Europe (left) and Scotland (right)

3.1.1 The Past

Dundee first established itself as an important commercial hub in the 16th century due to its proximity to the Baltic and North European shipping routes via the River Tay. The city has always had close ties to the river which provided it with rich transport and trade links (McCarthy 1995).

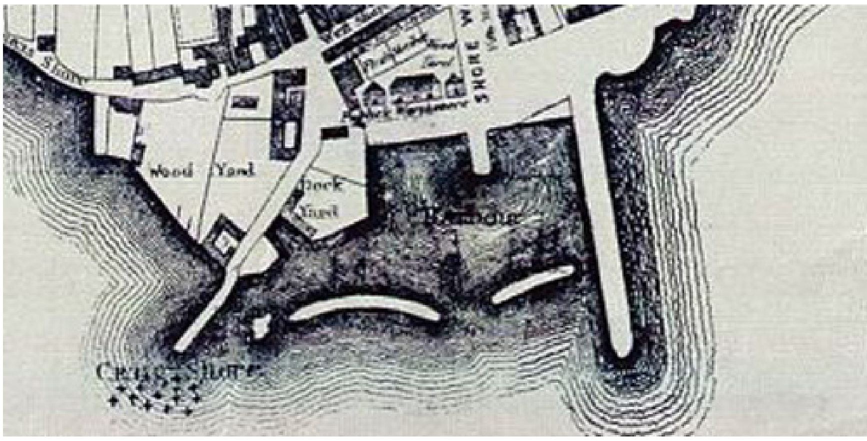


Figure 3.2 Dundee Waterfront 1793 (Crawford 1793)

The development of the docks on the current site continued throughout the 17th and 18th centuries but still remained comparatively small (Dundee City Council 2001). At the beginning of the 19th century the outbreak of the Napoleonic wars brought a period of industrial expansion of the city due to its role in the jute trade and the export of canvas and hessian (McCarthy 1995). By the 1830s “Dundee had changed from a trading port to the world centre for the jute processing industry” and the city and its port were rapidly expanding (Dundee Waterfront 2007). Figures 3.2 and 3.3 show how the city was changed by this industrial expansion.

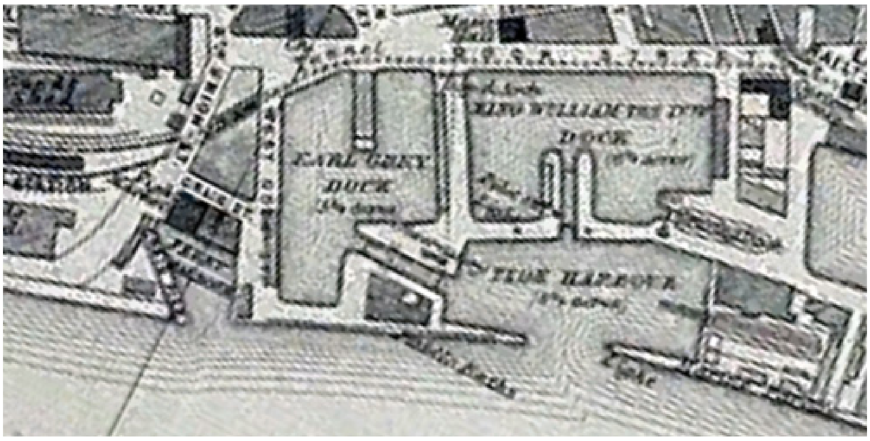


Figure 3.3 Dundee Waterfront 1893 (Mathew 1893).

The well known engineer Thomas Telford was appointed to design the required improvements to the existing Dundee harbour facilities. His designs included the addition of the King William IV Dock and the West Graving Dock on the site of the old tidal harbour. Over the next 100 years, more additions to the docks were made, including the Earl Grey Dock to the west and the larger Victoria Dock to the east, "moving the city further away from the waterfront" (Figure 3.3) (Dundee Waterfront 2007). The last dock, the Fish Dock was completed in 1900 and was followed by significant decline in the Jute industry, which had a major effect on the economy of the city (McCarthy 1995). In 1906 city planner James Thomson attempted to address the issue of what to do with the now increasingly under-used harbour area. His proposal included the construction of a large civic centre to the west and a road bridge to the Fife coast in the east (Figure 3.4). However, due to the outbreak of World War One, Thomson's plans were never implemented (Dundee Waterfront 2007).

Figure 3.4 James Thompson's undeveloped vision for Dundee

3.1.2 The Present

Figure 3.5 Dundee Waterfront 2007 (The GeoInformation Group 2007).

Dundee waterfront was largely untouched until 1960 when the City Council finally accepted a proposal to build a road bridge connecting Dundee to the Fife coast. Major construction work was performed on the waterfront area which included the filling-in of the former docks to provide a cheap land fall for the new bridge. Dundee's central waterfront became "a 1960s highway based solution for the Tay Road Bridge" (Scottish Executive 2006), unattractive buildings constructed in the 1970s, such as the Councils own offices in Tayside House and the Olympia Leisure Centre were to form part of a "multi-level, modernist, civic and commercial centre" which was never completed (Dundee Waterfront 2007). These developments left the city, which had at one time been so heavily entwined with the river, completely severed from the waterfront. Figure 3.6 shows the type of buildings and walkways which were developed during the 1960s. The entire development of Dundee at this time was performed on land that had been completely reclaimed either during the cities initial expansion in the last century or reclaimed to enable the developments undertaken during the 1960s including the landing point for the Tay Bridge. As can be seen access to the water is limited and the view of the river from the city is largely obstructed by the large buildings. All of the buildings shown here are to be demolished for the proposed development.

Figure 3.6 Dundee waterfront before the start of the proposed development.

The changes in the design of Dundee are also reflected in the changes to the city's population. From Figure 3.7 it is clear to see the rise and fall in Dundee's fortunes. These changes mirror the growth and decline of Dundee's waterfront and the docks.

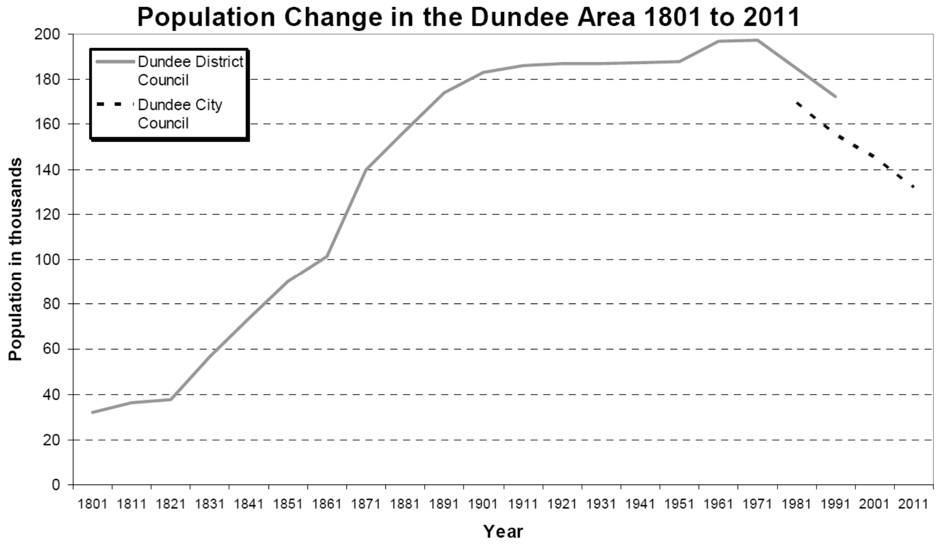


Figure 3.7 Population changes in Dundee from 1801 – 2011 (Dundee City Council 2004).

The exponential growth which occurred throughout the 19th century with the arrival and development of the jute industry, and the gradual tail off as the industry collapsed during the first half of the 20th century can be clearly compared to the changes in Dundee population. It can be seen that Dundee goes against the global trend of urbanisation, since the destruction of the harbour in the 1960s & 70s Dundee's population has continued to fall year on year. With declining economy and population it is possible that Dundee has already become a victim of unsustainable developments.

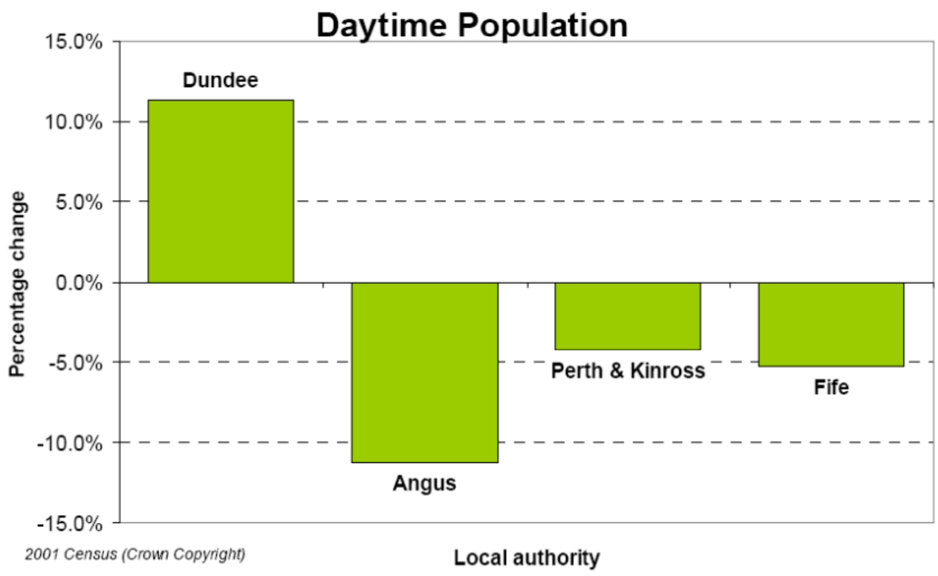


Figure 3.8 Daytime population changes for Dundee and surrounding regions (Dundee City Council 2004).

While the resident population of Dundee has continued to fall, the city's daytime population still draws heavily on the surrounding areas of Angus, Fife and Perth & Kinross (Figure 3.8). This shows that Dundee still remains "a vital City Region hub, providing employment and educational opportunities, as well as retail and leisure services" (Dundee City Council 2004) to the surrounding regions. As well as the provision of services Dundee also has the highest proportion of students of any city in Scotland although it does also have one of the lowest graduate retention rates (Dundee City Council 2004).

3.1.3 The Future

Figure 3.9 Dundee Waterfront Masterplan (Dundee City Council 2001).

In an attempt to re-connect the city with the waterfront Dundee City Council has released a redevelopment master plan. These plans include:

- the extension of the city centre down to the waterfront.
- the creation of a new grid based street pattern.
- improved provision for walking, cycling and buses.
- the reduction of the effect of cars and parking.
- the removal of some of the Tay Road Bridge ramps.
- the creation of a pair of east/west tree lined boulevards.
- provision of sites for a variety of mixed use developments.
- the formation of a major new civic space and re-opened dock.
- the provision of a new rail station and arrival square.

(Dundee City Council 2001)

It is hoped that the re-development will stop the large numbers of graduates and residents leaving the city by providing more jobs, better quality housing and a more attractive urban environment. Figure 3.9 shows the outline of the decided plots for the new Dundee waterfront development, the position of each of the plots has already been decided but the exact design of building and its use has not.

3.1.4 Reasons for Choice

It is clear from the historical planning decisions made in Dundee, especially during the 1960s and 70s that the city has suffered from some unsustainable decisions. Because of the failures of past developments in Dundee it is even more important that the re-development is sustainable and this has been identified by Dundee City Council who are actively assessing the sustainability of the new waterfront development (Gilmour et al. 2011). Dundee City Council have already identified with stakeholder consultation which indicators are important for the development and how many of these indicators can be measured. This provides a number of indicators which can be modelled within the new DST (Chapter 4). The waterfront development also occurs in an area where all of the current structures, with the exception of the historic ship and centre, are to be demolished, leaving a completely blank canvas on which the new development is to be built. This gives the most available options for the creation of different scenarios on which the S-City VT can be tested.

Chapter 4 Sustainability Indicator Modelling

The sustainability indicator modelling involves developing sub-models that define how each of the indicators vary over space and time. The S-City VT application is designed using a modular framework providing flexibility and allowing indicator models to be updated and refined as more data becomes available or different models are required. The S-City VT uses six indicators which were identified from a list of indicators that are already collected and used by Dundee City Council to assess the sustainability of the waterfront development (Gilmour et al. 2011). To reflect the three pillars of sustainability; economy, society and environment, two indicators from each aspect were chosen. The indicators selected; energy efficiency, air pollution, acceptability, housing provision, economic output and tourism were chosen as it was felt that models describing these indicators could be either identified or developed from existing sources (Figure 4.1).

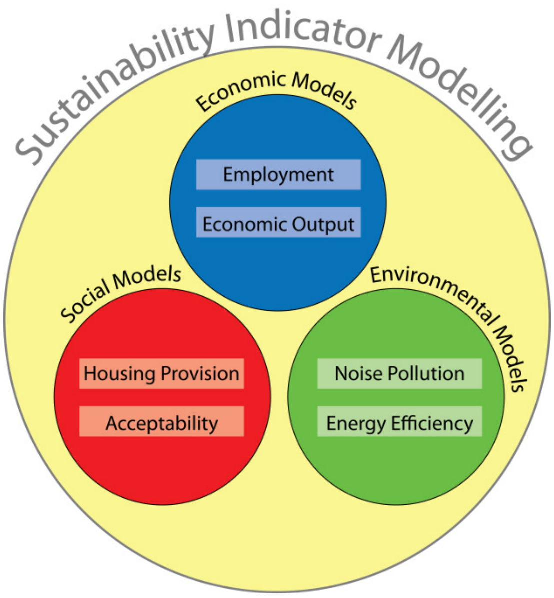


Figure 4.1 Indicator Models representing the three pillars of sustainability

During the course of the project tourism and air pollution were replaced with employment and noise pollution indicators. Dundee City Council identified a specific interest in the impact of traffic noise on how the public would view the new development. Specifically the traffic levels on the two main thoroughfares, on the north and south sides of the development, which would have to be crossed to access the new civic space may impact how the development was used. The tourism indicator was changed as although tourism data could be easily sourced from the city's tourism department, it was felt that levels of visitors could not be directly attributed to the waterfront as the main attractions in the city are not located in the waterfront development.

The sub-models are used to determine the indicator values for each square metre of a building (including floors) through time. These can then be summed to obtain a value for each building. A sustainability score for the entire development can then be calculated from the score for each building. The indicator models describe the temporal changes of each indicator and are derived from collected data or literature. For example, energy usage for buildings is determined using the industry standard National Calculation Method (BRE 2008) which provides the energy usage of a building based on its attributes, materials and seasonality.

Each of the indicator models were implemented using the C# programming language, the following sections describe the sub-models pertaining to each indicator in detail.

4.1 Energy

The energy use model is based on the Nation Calculation Method (NCM) which is the industry standard allowing energy efficiency and energy use of proposed buildings to be determined (BRE 2009). The NCM method takes into account a wide range of factors, including number of doorways, window glazing type, exterior construction, and number of floors etc, to produce a metric describing the energy efficiency of the building. A NCM report was developed using the NCM simplified building energy model tool (SBEM), representing the typical buildings in the development for a number of different options including external appearance and different mixes of building use. The NCM was selected to drive the energy model as it would be expected that any proposed building would have to submit a NCM report showing the energy efficiency and energy use of the building along with their design to the planning department. These data could then be imported to the S-City VT system meaning there is no extra work for the building designer and little extra work for the planners.

The NCM report gives the amount of energy a building will use per year and from this it was possible to calculate monthly energy use for each building. However to show the effect of the time of year on a building's energy use, it was necessary to determine how these monthly values would be weighted. To determine the effect of the time of year on a building's energy use, energy consumption data were sourced from the Department of Energy & Climate Change which shows the monthly energy consumption based on sector, e.g. residential, commercial or retail (BIS 2009). This data was used to create a set of weights for each month of the year depending on a building use.

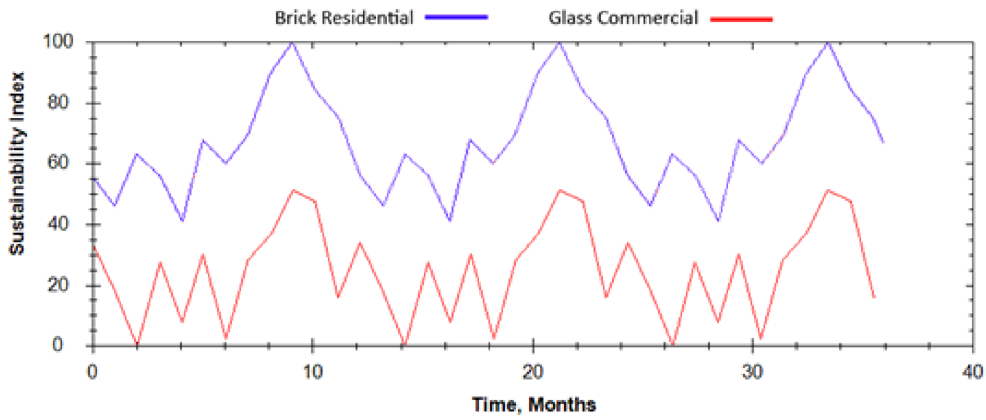


Figure 4.2 Graph showing temporal changes in sustainability index due to monthly energy fluctuations.

$$Energy\ use = \frac{annual\ energy\ use}{12} \times monthly\ weighting factor$$

Equation 4.1 Calculation of monthly energy use

A sustainability index is created from attenuated monthly energy use for each building through linear normalization to a 0-100 scale with 0 being worst and 100 being the best. The energy model's final output is therefore a month by month sustainability index for each floor of each building depending on the building material and its use. Figure 4.2 shows how the sustainability index changes as a function of time for two buildings with different proposed building material (glass and brick) and with different uses (commercial and residential).

4.2 Noise

The noise model is designed to calculate the levels of traffic noise "heard" by each building and can also predict the proportion of people that will find certain levels of noise a nuisance. Data about the projected traffic flows for the case study waterfront development were sourced from Dundee City Council's Dundee Waterfront Traffic & Signalling Report, as shown in Figure 4.3 (White Young Green 2007b).

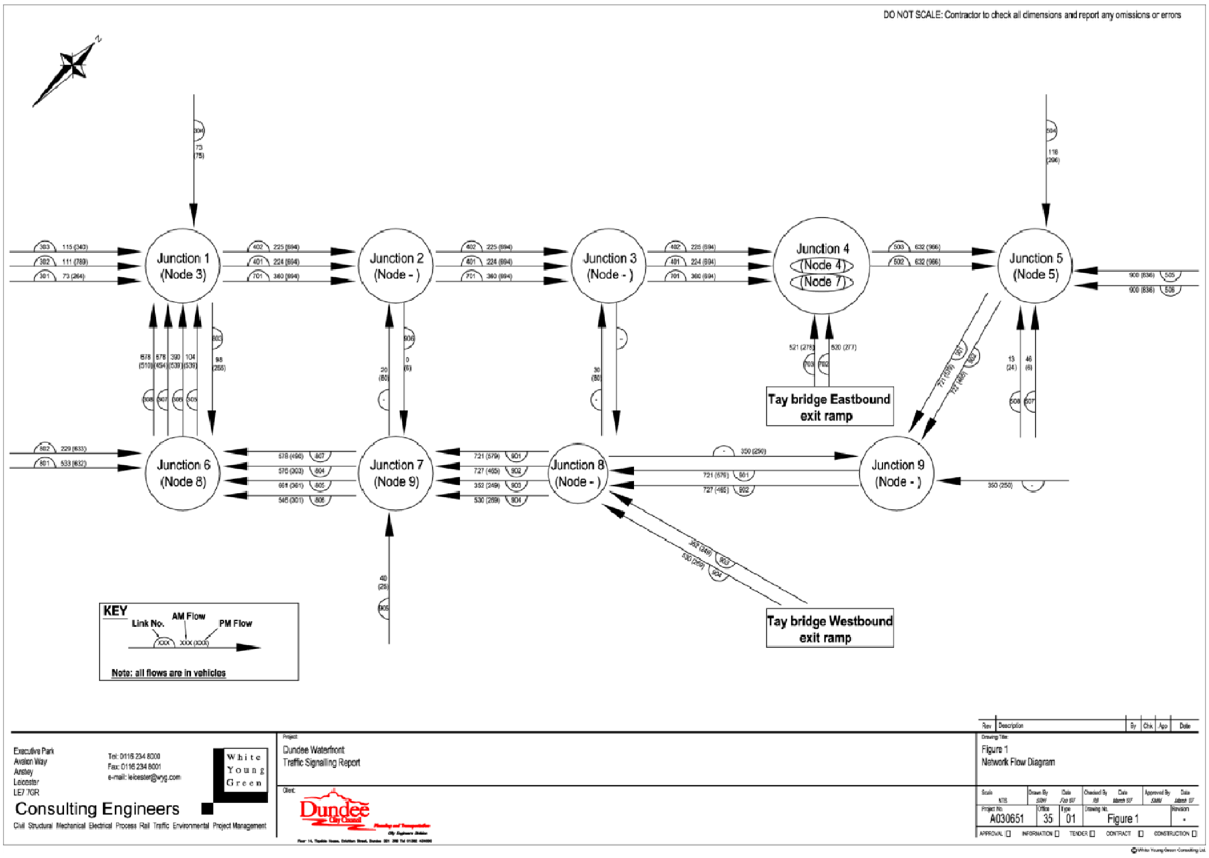


Figure 4.3 Projected traffic flows for Dundee Central Waterfront (White Young Green 2007a).

For each of the roads in the proposed development, a noise level is calculated using its projected traffic hourly traffic flow (Figure 4.4). This gives each road a basic noise level which corresponds to how loud, in decibels, the traffic noise would be if the listener were standing around 10 meters away from the road side.

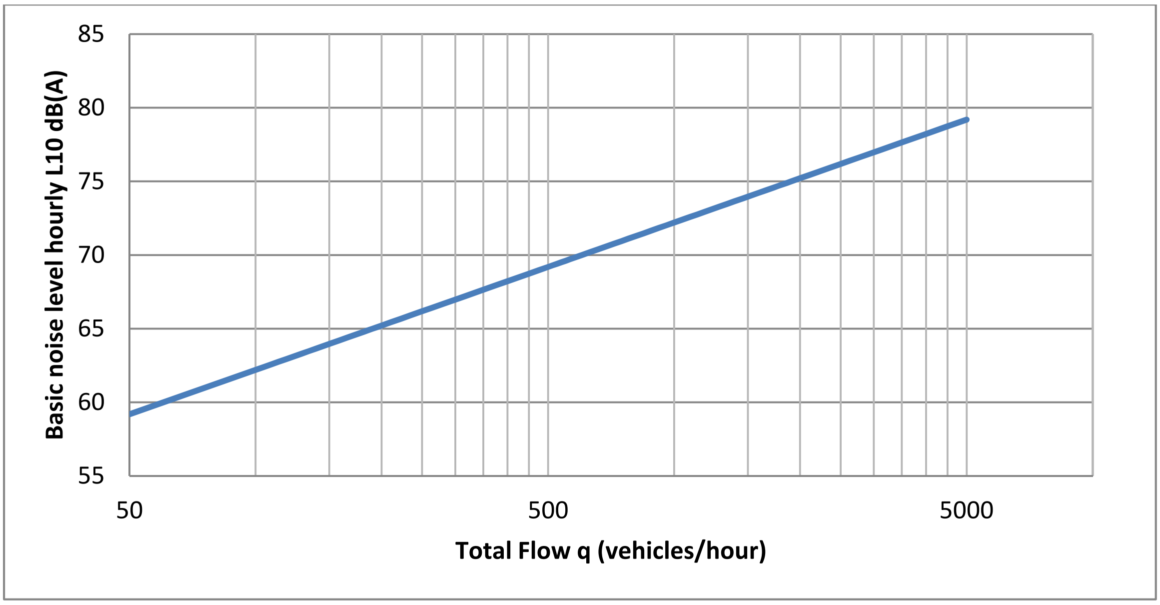


Figure 4.4 Prediction of basic noise level hourly L10 in terms of total hourly flow.

$$\textbf{Basic hourly noise level } L_{10} = 42.2 + 10\log_{10} q \; dB(A)$$

Equation 4.2 Calculation of basic hourly noise level (CRTN 1988)

Once each road has an associated noise level, it is possible to calculate how much of this noise will radiate to each building depending on the distance between the noise source and the building. For each building in the scenario, the closest distance from its centre to a line down the middle of each road is calculated. This is achieved using a simple point to line equation (Figure 4.5):

$$\textbf{distance } d = \frac{|(B.x - A.x)(A.y - C.y) - (A.x - C.x)(B.y - A.y)|}{\sqrt{(B.x - A.x)^2 + (B.y - A.y)^2}}$$

Equation 4.3 Calculation of shortest point to line distance

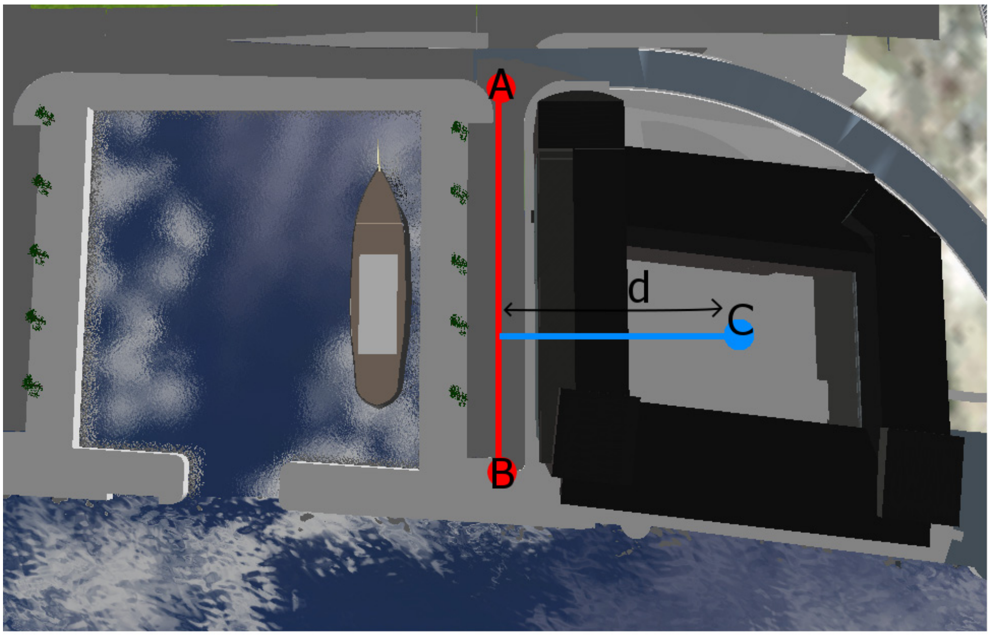


Figure 4.5 Distance d between building C and road AB

Each building in the development is now associated with a list of distances representing how far away it is from each road. Once a list of distances has been equated for each building the sound level from each road is obtained by correcting the basic noise level for that road using the distance between the building and that road. The equation also includes the height of the listener to calculate the shortest slant distance to the noise source so it is possible to determine the differences in noise level at different building levels. The model also allows a threshold value to be entered beyond which the noise level will not be calculated. This is purely for computational reasons as calculating noise levels which have no effect on the combined noise level would be inefficient. This gives a noise level for each road in A-weighted decibels (dB(A)):

$$\boldsymbol{Noise\ Level\ Correction} = -\mathbf{10}\ \mathbf{log_{10}}(\boldsymbol{d'}/\mathbf{13.5})\ \boldsymbol{dB}(\boldsymbol{A})$$

$$\boldsymbol{where\ d'} = \boldsymbol{shortest\ slant\ disatnce\ from\ the\ road}\ [(\boldsymbol{d} + \mathbf{3.5})^{\mathbf{2}} + \boldsymbol{h}^{\mathbf{2}}]^{\frac{\mathbf{1}}{\mathbf{2}}}$$

Equation 4.4 Calculation of noise level correction (CRTN 1988)

At this point each of the buildings will have a list of corrected noise levels representing the noise levels which can be heard from each road. To find the total noise level received by the building the corrected noise from each road must be summed. As the relationship between noise levels is not linear the noise levels are combined using the following equation.

$$\boldsymbol{Total\ noise\ level} = \mathbf{10}\ \mathbf{log_{10}}[\sum_{\mathbf{1}}^{\boldsymbol{n}} \boldsymbol{Antilog_{10}}(\boldsymbol{L_n}/\mathbf{10})]\ \boldsymbol{dB}(\boldsymbol{A})$$

$$\boldsymbol{where\ Ln} = \boldsymbol{noise\ level\ calculted\ for\ road\ n}$$

Equation 4.5 Calculation of total noise level from multiple noise sources (CRTN 1988)

Each building will now have a noise level value representing the total level of noise that could be heard in that buildings position in the development. This value is normalised to a 0-100 scale to allow for later visualisation and weighting. Rather than linear normalisation the estimation of traffic noise nuisance equation is used, this calculates the percentage of people that will be bothered by a specific level of noise.

$$\%\ \boldsymbol{Bothered} = \frac{\mathbf{100}}{(\mathbf{1} + \boldsymbol{e}^{-\boldsymbol{\omega}})}$$

$$\boldsymbol{where\ \omega} = \mathbf{0.12}\ (\boldsymbol{L\ dB}(\boldsymbol{A})) - \mathbf{9.08}$$

$$\boldsymbol{L} = \boldsymbol{Total\ calculated\ noise\ level}$$

Equation 4.6 Calculation of proportion of people bothered by observed noise level (Highways Agency 1994)

4.3 Housing Provision

The Housing provision model calculates the proportion of the building designated as residential space. A building which is designated for completely residential usage will have a value of 100 whereas mixed use buildings will have varying proportions of residential space. This will give a sustainability index of 0-100 for each building or floor of a building based on the area of residential space assigned which is directly comparable to the results of the other sub-models. This indicator was selected due to a particular issue which was identified in Dundee around the availability and proportion of housing/residential space in the planned waterfront area, a high proportion of housing provision may not be indicative of higher sustainability in other developments.

4.4 Acceptance of building appearance and usage

The acceptance of a building in a development refers not only to the building's aesthetic acceptance but also to the acceptance of the buildings use. It is important that the buildings to be constructed are accepted by the people that will eventually live or work in and around the development. To enable the model to be created it was necessary to collect data representing the acceptance people had towards certain types of buildings and building uses. As the Masterplan for Dundee had already been developed, it was possible through discussion with Dundee City Council to determine the possible building materials and uses which were under review. The Council's vision for the waterfront was one which would set it apart from other waterfront developments in Scotland, primarily the Council wanted to stay away from the glass and steel architecture that dominates Glasgow's waterfront.

4.4.1 Analysis of building appearance.

The first part of the data collection was to determine if there was a significant difference between people's preferences for glass and steel architecture and a more traditional pastel appearance, typical of Baltic ports. This was achieved by conducting an online questionnaire which showed examples of different brick and glass buildings, using realistic and virtual representations, and allowed the user to choose which building they preferred. Examples of the types of building representations for both parts of the survey are shown in Figures 4.6 & 4.7. While photographs have been used shown to adequately simulate environments (Stamps 1990) there has been some discussion about the ability of virtual environments to adequately reflect the real environment (Daniel & Meitner, 2001). However previous research performed on choice decisions using virtual environments (Laing et al., 2004; Laing et al.,2009) shows that virtual environments are a viable method of obtaining peoples preferences in urban environments. A further experiment detailed in Section 7.8, details how the validity of the virtual environment used in S-City VT was confirmed.

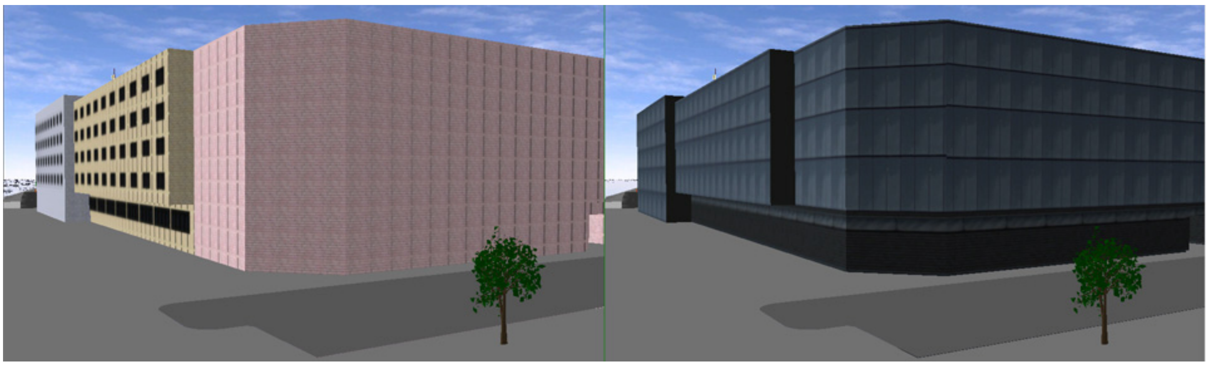


Figure 4.6 Example representation of virtual buildings used in building appearance survey

Figure 4.7 Example representation of real buildings used in building appearance survey

Table 4.1 Descriptive statistics resulting from building appearance survey.

	Virtual Q1	Virtual Q2	Virtual Q3	Virtual Q4	Virtual Q5	Real Q1	Real Q2	Real Q3	Real Q4	Real Q5	Real Q6	Real Q7
Number	106	106	106	106	106	106	106	106	106	106	106	106
Mean	2.95	2.90	3.42	3.12	3.53	3.30	2.67	3.44	2.70	2.82	2.86	3.35
Median	2.50	2.50	4.00	4.00	4.00	4.00	2.00	4.00	2.00	2.00	2.50	4.00
Mode	2	4	4	4	4	4	2	4	2	2	2	4
Maximum	5	5	5	5	5	5	5	5	5	5	5	5
Minimum	1	1	1	1	1	1	1	1	1	1	1	1
Std. Deviation	1.533	1.454	1.379	1.446	1.388	1.462	1.350	1.295	1.500	1.308	1.245	1.273
Skewness	.048	.032	-.475	-.141	-.712	-.317	.459	-.422	.394	.235	.123	-.318
Kurtosis	-1.585	-1.523	-1.133	-1.465	-.906	-1.405	-1.115	-1.035	-1.381	-1.202	-1.264	-1.076

The appearance survey was based on a Likert scale from 1 to 5, with 1 and 2 defining a strong and slight preference for brick buildings respectively, 3 defining no preference and 3 and 5 defining slight and strong preference for glass buildings respectively. The mean for each question is generally just above or below the centre of the scale, suggesting that there were no questions which provoked a particularly strong preference for either glass or brick buildings. The relatively small standard deviations, low skewness and platykurtic kurtosis characteristics for each question also support this.

Determining if there was a significant difference between the participants preference for brick or glass buildings.

A concurrent experiment, documented in Section 7.8, showed that in this case, there was not a significant difference between the participant's choice of preferred building when the buildings were represented by real or virtual images. Because of these findings, the datasets were be combined to determine if there was an overall preference for one type of building. Each participant's survey answers were scored ranging from -2 (strongly prefer brick) to 2 (strongly prefer glass). The scored results were then summed for each participant to create an overall score for each user. This gave each participant a score between -24 and 24 with positive results representing a lean towards glass buildings and negative results representing a lean towards brick buildings, giving an expected median value of 0. A sign test was performed on these results to determine if there was a significant deviation from the median in either direction.

Table 4.2 Results of sign/binomial test

Null Hypothesis: There is no overall preference for glass or brick buildings giving an expected median of 0.

	Category	Number	Proportion.	Test Prop.	Asymp. Sig. (2-tailed)
Brick Preferred	<= 0	50	.47	.50	**.627**[a]
Glass Preferred	> 0	56	.53		
Total		106	1.00		

The sign test result of p=0.627 for the group that preferred brick shows that there was no significant deviation from the median value towards brick buildings, also the result (1-0.627) for the group preferring glass is still outside the 5% confidence level.

These results suggest that the participants, as a group, had no significant preference toward brick or glass buildings. This allowed these building types to carry equal weighting in the model.

4.4.2 Analysis of building use

The second part of the data collection was to determine if there was a significant difference between people's preferences for different building uses. This was achieved by conducting an online questionnaire which used a ranking system where the participant was asked to rank possible building uses in order of preference. The four possible building uses, again due to their importance in the current development, were defined as commercial office space, retail units, cafe/bar/restaurant and residential space.

Table 4.3 Descriptive statistics resulting from building use survey

	rank1	rank2	rank3	rank4
Number	106	106	106	106
Mean	2.9057	2.6509	2.6415	1.8019
Median	3.0000	2.5000	2.0000	1.0000
Mode	3.00	2.00	4.00	1.00
Std. Deviation	.79915	.93648	1.18875	1.19060
Skewness	-.855	.117	-.032	1.117
Kurtosis	.756	-1.016	-1.563	-.459

The mean values for each rank (Table 4.3) show some differences, especially between rank 1 and rank 4, which seems to show that the proportions of each building type in each rank are not equal. The relatively low standard deviation of each rank suggests that the answers to this question are not well spread out, again suggesting that the participants may have clear preferences regarding building uses, which is supported by the relatively high skewness characteristics, especially in rank 1 and rank 4.

If the participants had no preference between the building uses at each rank the proportions chosen at each rank would be equal. To determine if this is the case a Friedman test was performed on the mean rank of each building use, with the null hypothesis being that the mean ranks will be equal.

Friedman test

Table 4.4 Observed ranking of building use

	Mean Rank
Commercial	3.37
Retail	2.51
Leisure	1.54
Residential	2.58

Table 4.5 Test Statistics resulting from building use survey

Sample Size	106
Chi-Square	107.264
df	3
Significance.	.000

The results of the Friedman test (Tables 4.4 & 4.5) show that there is a significant difference between how the users ranked the different building uses. Combined with post-hoc analysis of the results it is possible to model the acceptability building uses in the following order:

1) Leisure (highest ranked);

2) Retail & Residential (equal ranked);

3) Commercial (Lowest Ranked);

The acceptability model scores each building or floor based on these results, thus leisure will score 3, retail and residential will score 2 while commercial will score 1. These results are then summed and normalised linearly to provide a sustainability index for each building in the range 0 -100, where 0 is the lowest, again this allows it to be compared to the other sub-model outputs.

4.5 Economic worth

The economic worth of a building is a reflection of how financially sustainable each building lot is. Each of the buildings in a development will have a different economic worth depending on its use, e.g. commercial, residential, retail or leisure and also depending on whether the building is to be sold or rented. The economic model utilises a discounted cash flow calculation to determine the worth of a buildings current cash flow for a specific point in time. The calculation uses a discount rate which allows the cash flows to be discounted back to their present worth:

$$\text{Net Present Value} = CF_0 + \frac{CF_1}{(1+r_1)} + \frac{CF_2}{(1+r_2)^2} + \cdots + \frac{CF_t}{(1+r_t)^t}$$

Where

CF = cash flow for that year.

r = discount rate for that year.

t = the year.

Equation 4.7 Calculation of net present value (PV)

Discounting Capital Costs

In Equation 4.7, the capital cost for the construction of the first building is represented by CF_0. Capital costs of subsequent buildings will be discounted to this point in time e.g. the capital cost of a building built two years after the initial building would be discounted using $\frac{CF_2}{(1+r_2)^2}$

Discounting Income

Each building in the development will have a site preparation, where an existing building is demolished and infrastructure for the proposed building put in place and a construction phase where the building is physically developed. During this time the cash flow in for that period is taken as 0 as the building would not yet be sold or rented and as yet there are no maintenance costs. The simulation is able to reflect the differences between cash flows for rented and sold buildings. Buildings which are sold will take a large income at the point of sale. As the building has been sold, further cash flows for this building will be 0. The discount factor will also apply to the sale income so for two buildings of equivalent value, a building sold in year one will have a higher present value than building sold in year 10. As the building has been sold the upkeep and maintenance of the building will be borne by the buyer and so it is not modelled here. Buildings which are rented will take a smaller income every year. Rented buildings may have a rent free period, to encourage tenants, and will have a lay period between leases, during which times the cash flow for that period will be 0. A discount factor is applied to the yearly income to determine its present value, again based on the construction year of the first building. The impact of the discount factor for rented and sold building can been seen in Figures 4.8 & 4.9.

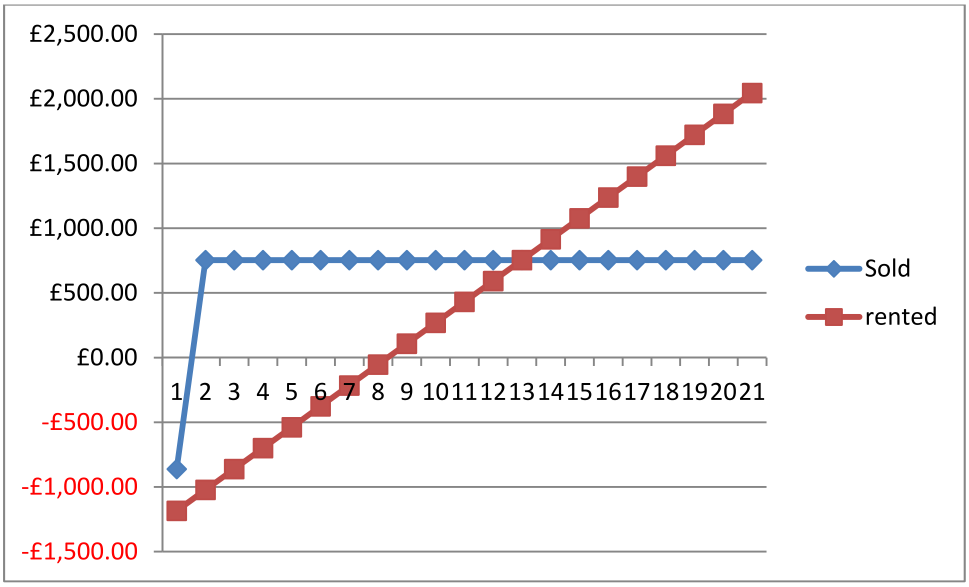


Figure 4.8 Comparison of a sold and rented building completed in year 0. With 0% discount rate applied.

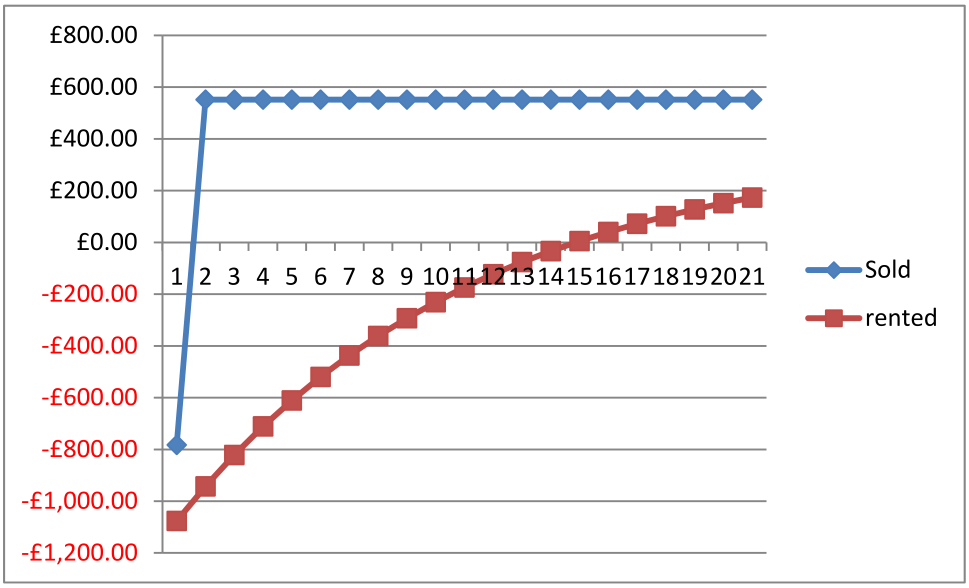


Figure 4.9 Comparison of a sold and rented building completed in year 0. With 10% discount rate applied.

Estimating Cost/Income

The initial cost of the buildings are calculated using the building type (e.g. residential, commercial, retail, social) and the cost per square metre for that type of building. The income from sale or rent is likewise calculated using the projected income for that type of building. These values were sourced from the SET economic report (Buchanan 2006) on the waterfront development and are outlined in Table 4.6 below.

Table 4.6 Rental or Sale income for different building uses

Building type	Capital Cost	Sale / Rental Value
Residential	£861.11 per m^2	Sale £1614.59 per m^2
Commercial	£1184.03 per m^2	Rent £161.46 per m^2 per month
Leisure	£1345.03 per m^2	Rent £161.46 per m^2 per month
Retail	£1130.21 per m^2	Rent £134.55 per m^2 per month

Combined Development

To give an indication of the sustainability of an entire development, the data for each building are normalised to a scale from 0 -100 using linear normalisation. The DST compares all input scenarios and 0 on the scale represents the lowest ever negative cumulative discounted cash flow (cost) in all the scenarios. Similarly 100 represents the highest positive cumulative discounted cash flow (income). The combined index for the development is the total of all the indices for each building at any point in time.

Figures 4.10 to 4.14 show the sustainability index of a number of different scenarios of building sale or rent over a 5 year period. These figures not only show the impact of the discount factor and the choice of rental or sales income on the whole development, but also show the impact of the different building phases which can be clearly seen by the steps in each graph.

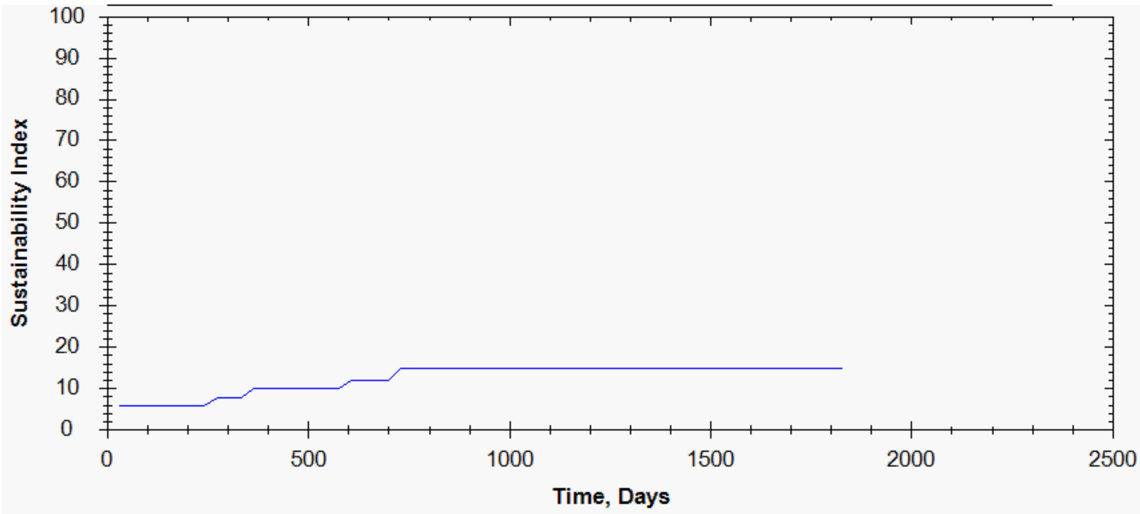


Figure 4.10 Total PV for 5 building development, all buildings sold as built.

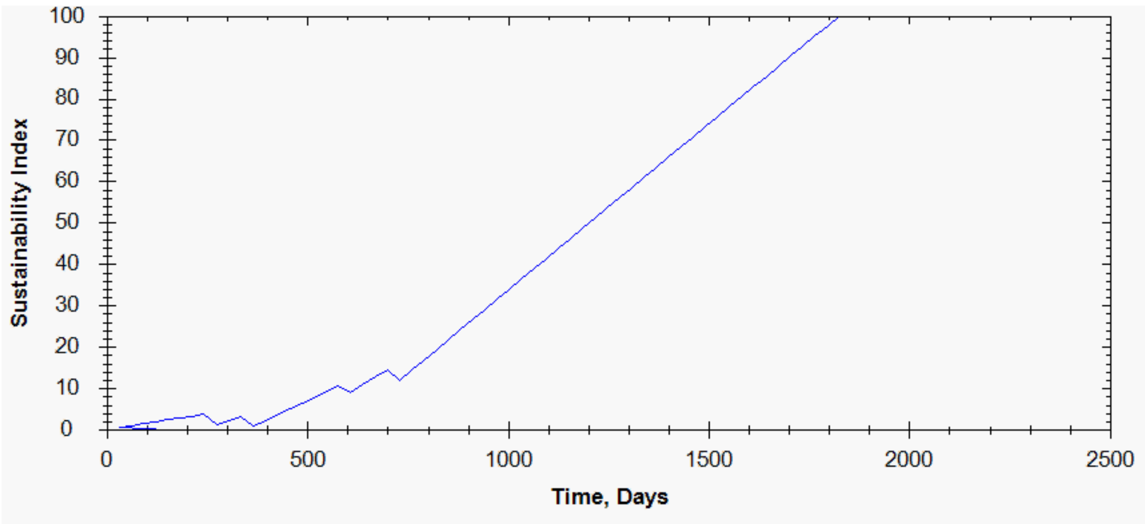


Figure 4.11 Total PV for 5 building development, all buildings rented as built with a 0% discount rate.

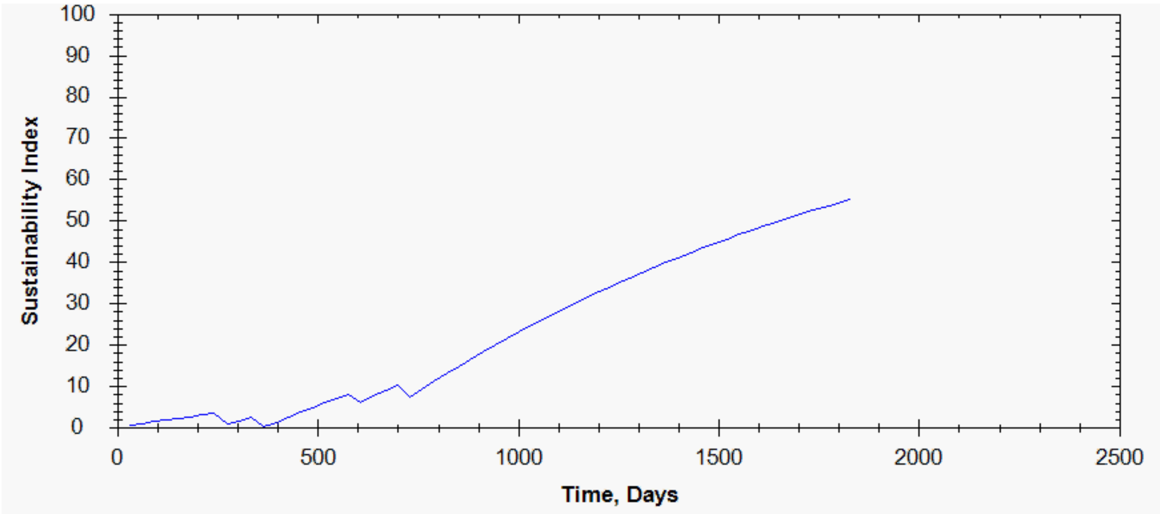


Figure 4.12 Total PV for 5 building development, all buildings rented as built with a 20% discount rate

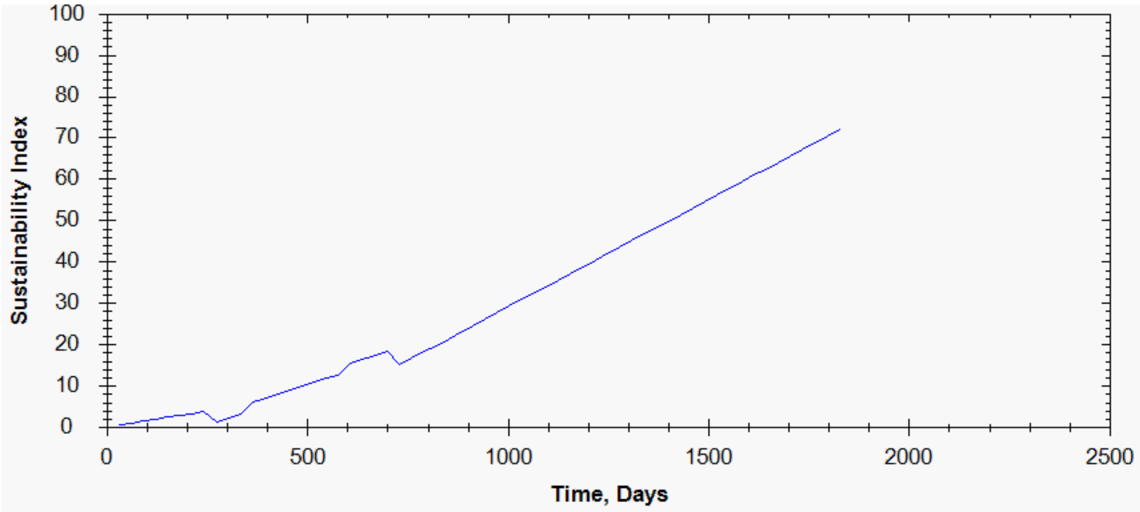


Figure 4.13 Total PV for 5 building development, mixed sale and rental with a 0% discount rate.

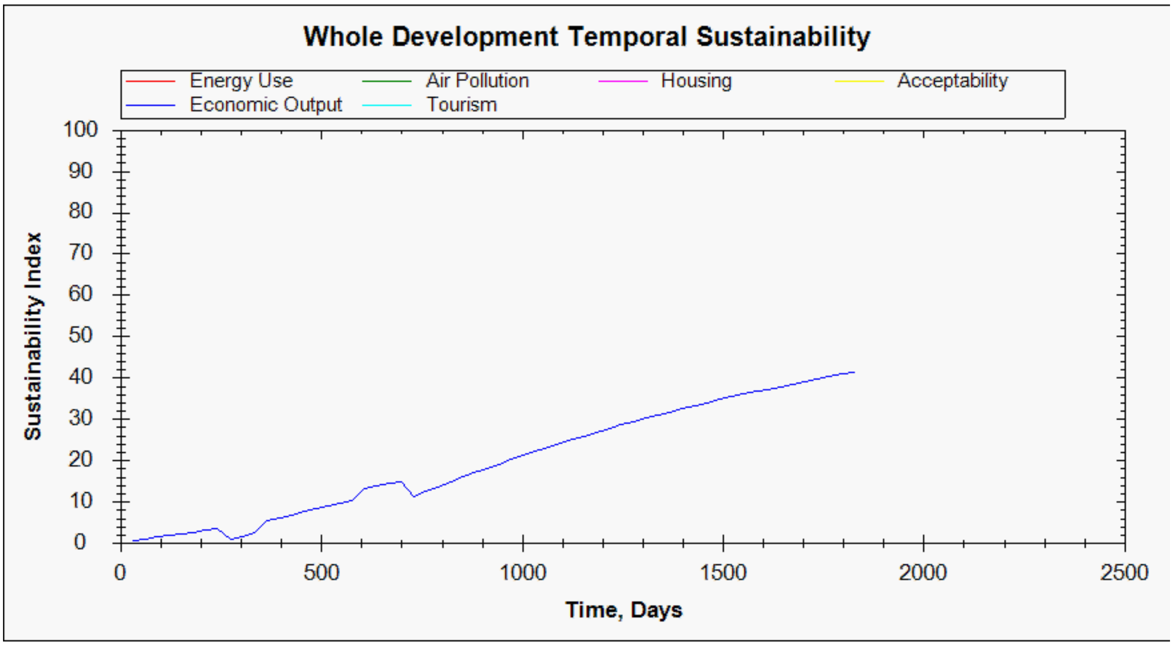


Figure 4.14 Total PV for 5 building development, mixed sale and rental with a 20% discount rate.

4.6 Employment

The Employment model uses existing information regarding different building uses (e.g. commercial, leisure etc) and building sizes to provide the likely number of jobs a specific building might create or sustain. These values were sourced from the SET economic appraisal on the waterfront development and are outlined in Table 4.7.

Table 4.7 Employment-Floorspace Ratios (Buchanan, 2006)

Floorspace Usage	M2 per employees
Commercial	15
Retail	20
Leisure	10
Residential	0

The maximum and minimum values are then mapped onto 0-100 and linearly interpolated.

4.7 Summary

The indicators used were selected to reflect the three pillars of sustainability and because it was believed that existing models or data to drive these models would be widely available. This resulted in some of the models being more complex than others. The noise pollution model, for example, is based on a number of equations which define noise levels heard within the virtual environment, whilst the housing provision model is simply based on the predicted proportion of residential space in a building. This range of model complexity, scale and units reflects the complexity of sustainability assessment in general and highlight the difficulty in creating a holistic DST. The sustainability indices derived from the output of the indicators sub-models are either aggregated using ANP, presented in the next chapter, for use in the blending technique or they are preserved for use in the other visualisation techniques presented in Chapter 8.

Chapter 5 Multi Criteria Sustainability Assessment

One of the problems with sustainability assessment, as highlighted in Chapter 2, is involving the views and experiences of a wide range of stakeholders. As stakeholder views are often in conflict, with one stakeholder placing more importance on a specific aspect (Social, Environmental or Economic) or indicator than another, it is important that these differing opinions be identified and included in the analysis (Geldof 2005). This, combined with the range of issues, interests and levels of decision making ability of the stakeholders makes the decision process extremely complex (Scheffran 2006). Many of the traditional methods of aggregating indicator values, such as Multi Attribute Utility Theory (MAUT), lack transparency leaving the users in a position where they do not fully understand how the resulting weightings have been derived (Dodgson et al. 2009; Paracchini et al. 2008). Because of the need for transparency, a multi criteria decision analysis method which would not only provide a transparent method of weighting the indicators but also a method which allows the users to use their own knowledge or personal feeling to have an effect on how the indicators are measured. The ANP method's use of pair wise comparison between sets of indicators seems to fulfil these requirements.

5.1 The Analytical Network Process

The Analytical Network Process (ANP) uses interactive network structures which give a more holistic representation of the overall problem (Saaty 2006). Components of the problem are connected, as appropriate, in pairs with directed lines simulating the influence of one component over another. The components in a network may also be regarded as elements that interact and influence each other in regard to a specific attribute. (Saaty 2006). ANP allows cross-cluster interactions as well as inter-relationships between elements. It is structured naturally and allows for a more realistic representation of the problem, but its main strength lies in providing the user with the ability to include their own personal knowledge and opinions about an interaction through the use of pair-wise comparisons (Saaty 2006; Bottero et al. 2007). The ANP method allows the relationships between the sustainability indicators to be described, and the indicators weighted and prioritised, in a transparent manner, as expressed by a specific stakeholder.

To perform an ANP analysis, the decision maker must identify the network through analysis of the problem to be solved. The decision maker must identify the clusters, elements and the relationships and interactions between them (Bottero et al. 2007). S-City VT allows the user to identify these relationships using an interface by which they can apply the ANP method to the indicators being modelled, thus defining the network that connects them. The ANP model interface allows the user to make judgements about the relative influence of each indicator of the model over each other indicator, using pair-wise comparison from the fundamental scale used by ANP (Table 5.1).

Table 5.1 Saaty's fundamental scale for ANP

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
3	Moderate Importance	Experience and judgement slightly favour one activity over another
5	Strong Importance	Experience and judgement strongly favour one activity over another
7	Very strong Importance	An activity is favoured very strongly over another; its dominance is demonstrated in practice
9	Extreme Importance	The evidence favouring one activity over another is of the highest possible order of affirmation.
2,4,6,8	For compromise between the above values	Sometimes one needs to interpolate a compromise judgement numerically because there is no good word to describe it
Reciprocals of above	If activity i has one of the above values assigned to it when compared with activity j, then j has the reciprocal value when compared to i.	A comparison mandated by choosing the smaller element as the unit to estimate the larger one as a multiple of that unit
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining n numerical values to span the matrix
1.1 – 1.9	For tied activities	When elements are close and nearly indistinguishable, moderate is 1.3 and extreme is 1.9

Figure 5.1 shows one of the interfaces by which the users can define to what degree they feel one indicator will influence another through the use of a simple numeric input box. In this case the user is expressing the influence of the social indicators housing provision and acceptability, it can be seen that this user has rated housing provision as being four times as important as acceptability.

Figure 5.1 Pair wise comparison of social indicators

When a comparison matrix has been created the elements must be prioritised, which is achieved by calculating the eigenvector, normalised priority weights, of each attribute. (Schniederjans 2004). These eigenvectors are then combined in the supermatrix where every interaction is described in terms of every element it interacts with (Saaty 1999).

5.2 Eigenvector calculation

Chapter 2 showed the process by which an ANP analysis is performed; one issue which arose during the implementation of the ANP process in S-City VT was the calculation of the prioritised list of elements through the use of eigenvectors. Saaty's original description of the ANP, and its predecessor the AHP methods suggests the use of an approximate eigenvector calculation. It was noted that the methods described in many papers which use ANP to calculate eigenvectors do not fit the mathematical definition of eigenvector.

Saaty & Vargas (2006), Coyle (2004) and Schniederjans (2004) suggest the eigenvectors be calculated by normalising each column then normalising the total of each row as shown in Figure 5.2.

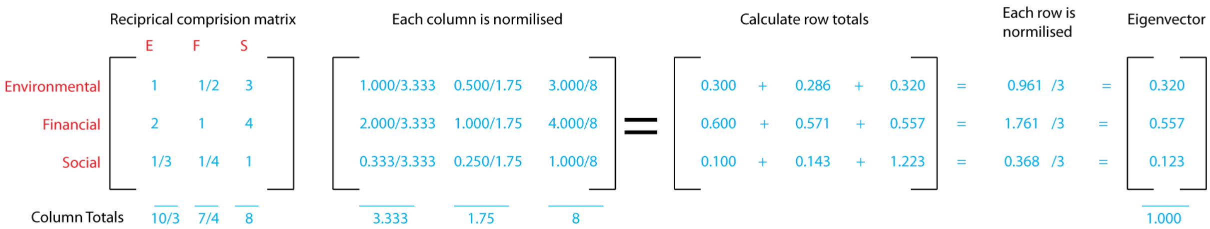


Figure 5.2 Approximate calculation of eigenvectors

To determine if there was a significant difference between the two methods, the approximation method suggested by Saaty and the standard numerical method of calculating eigenvectors was compared. An eigenvector calculator was developed as part of S-City VTs ANP model using example code from Numerical recipes (Press et al. 2007), which would calculate the eigenvectors using standard mathematical algorithms (Reduction to Heisenberg form and QR algorithm) (Figure 5.3). When the results were compared it could be seen that there was very little difference (<1%) between the approximation and the mathematical calculation suggesting that the approximation of the eigenvectors using Saaty's suggestion is appropriate. The use of the mathematical algorithms to solve the eigenvector are quite complex and their implementation contains many more lines of code than the much simpler approximation method; because of this the approximation method has also been implemented in S-City VT ANP model. This makes the priority creation from the pairwise comparisons more efficient, and more importantly comparable with other ANP implementations which will use the approximation method described by Saaty.

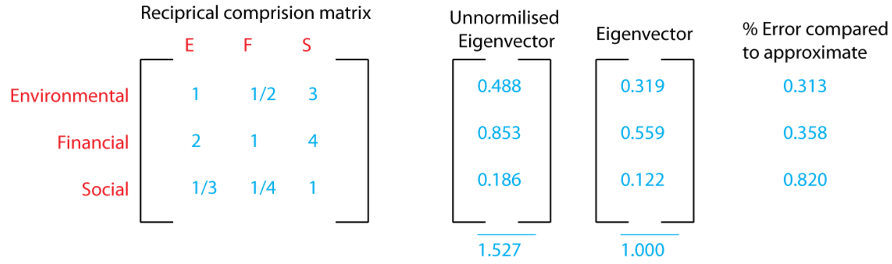


Figure 5.3 Mathematical calculation of eige vectors

5.3 Creating the Supermatrix

The supermatrix that is created via this process is known as the initial or un-weighted supermatrix as it does not yet express the weightings of the overall clusters (Saaty 1999;Saaty 2006). A pair-wise comparison matrix must be created to represent the relationship between the clusters, in this case environmental, financial and social. The S-City VT ANP component also includes an interface for each cluster of indicators (social, environmental and economic) allowing the user to express at a higher level how important any single aspect of sustainability is to them. To illustrate this process, pairwise comparisons of the top-level indicator network is given in Figure 5.7, here it can be seen that this stakeholder rates economic factors 12 times more important than social factors for the environmental indicators.

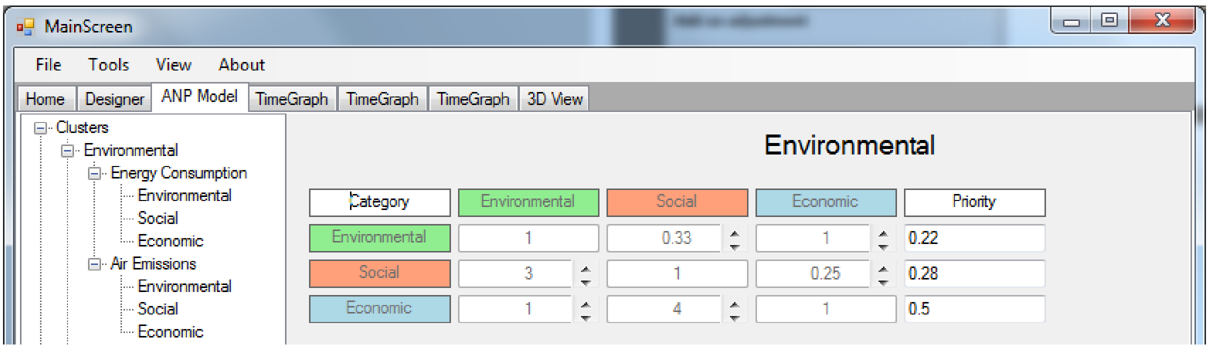
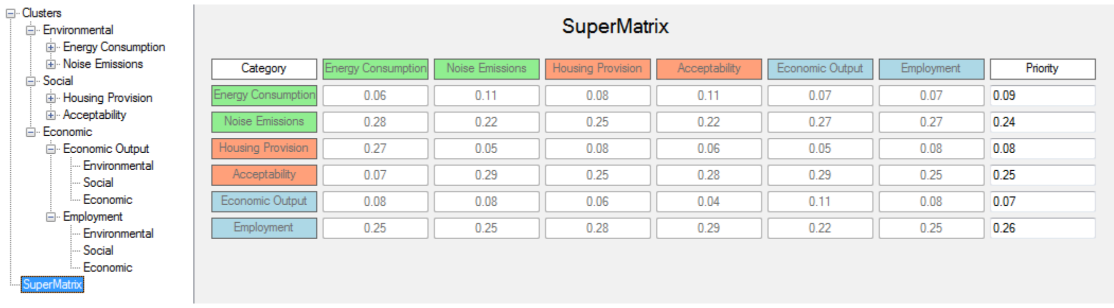


Figure 5.4 S-City VT Dialogue for setting ANP cluster weights

The final priorities for the cluster are also shown to the user allowing them to modify their pair wise comparison and see the changes immediately if they feel the final priority does not reflect how they actually feel about the influence of that particular cluster.

Once this has been completed the calculated eigenvector is applied to the un-weighted supermatrix, resulting in a final weighted supermatrix. The eigenvector calculated from the weighted matrix will give the decision maker the prioritised list of elements (Figure 5.5).



Category	Energy Consumption	Noise Emissions	Housing Provision	Acceptability	Economic Output	Employment	Priority
Energy Consumption	0.06	0.11	0.08	0.11	0.07	0.07	0.09
Noise Emissions	0.28	0.22	0.25	0.22	0.27	0.27	0.24
Housing Provision	0.27	0.05	0.08	0.06	0.05	0.08	0.08
Acceptability	0.07	0.29	0.25	0.28	0.29	0.25	0.25
Economic Output	0.08	0.08	0.06	0.04	0.11	0.08	0.07
Employment	0.25	0.25	0.28	0.29	0.22	0.25	0.26

Figure 5.5 Resulting supermatrix giving priorities/weightings for each indicator value

In a traditional ANP analysis the decision maker would perform this analysis for each scenario providing each scenario with a score which can be used to determine which scenario is the most suitable, in this case the most sustainable. However, this would only be appropriate if there are a set number of scenarios, and also only be practical if the number of scenarios is small as performing the analysis for a large number of scenarios would quickly become tedious. S-City VT has been designed to be as flexible as possible, allowing the stakeholder to use the scenario designer to create any number of scenarios. To allow the ANP method to be applied to an unlimited number of scenarios, the scenarios are not scored using the priorities but are instead the prioritised list of elements which are derived from the ANP analysis are used to weight the actual indicator values modelled for each scenario. These weighted indicator values can then be utilised in the sustainability assessment to quantify the sustainability index (aggregated or per indicator). Chapter 8 describes visualisation techniques to convey the aggregated and per indicator sustainability index.

5.4 Summary

ANP allows the indicator values produced by the sustainability models to be weighted by the stakeholders in what is a relatively transparent manner. Chapter 8 describes how this process is coupled to the modelling components (Chapter 4) and how the weighted sustainability scores or indices are then passed onto the visualisation techniques and projected on to the 3D environment (Chapter 7) through the creation of the S-City VT framework.

Chapter 6 Scenario Design

6.1 Scenario appearance

As identified in the requirements for the decision support system, there is the need to allow a great amount of freedom and flexibility in the creation and modification of possible future scenarios to allow decision makers to perform "what if" analysis on the impact of their decisions. The scenario designer fulfils this requirement in the S-City VT system. The Scenario designer forms the first stage in the creation of the virtual development; it is designed so that a masterplan of the proposed development can be created or interpreted from an existing 2D plan. The tool allows stakeholders to design the physical structure of the environment in a virtual space through a simple drag and drop interface allowing the components of the development to be moved into the user's desired position.

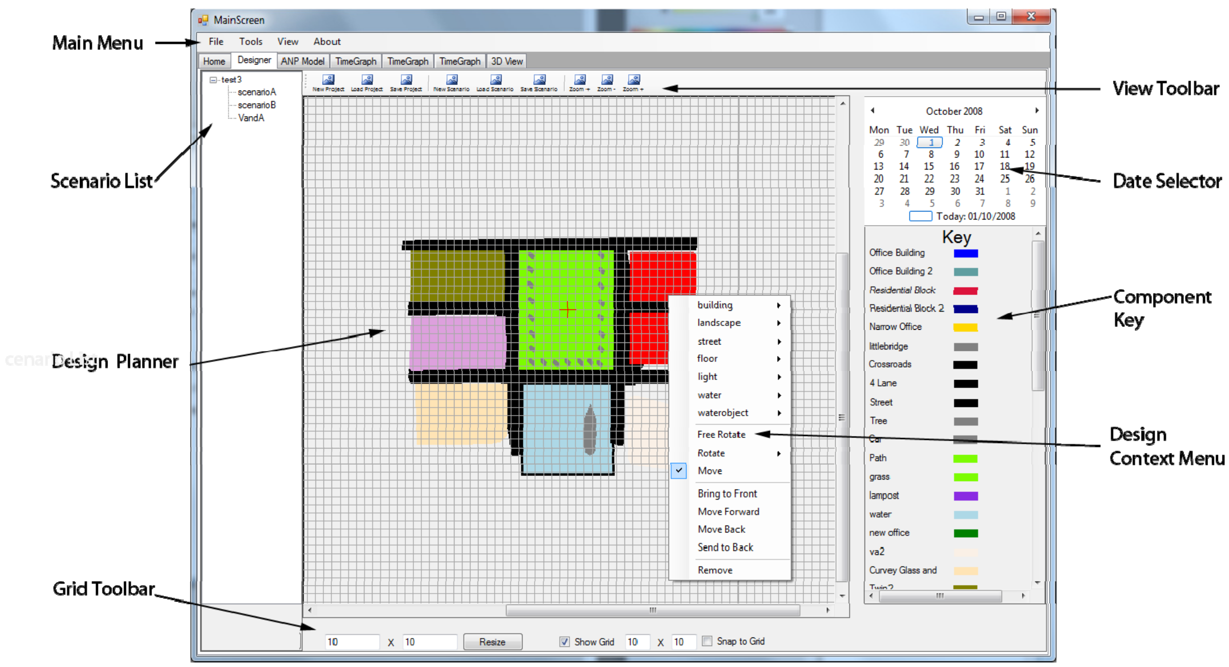


Figure 6.1 S-City VT Scenario Designer

Figure 6.1 shows an overview of the scenario designer screen and some of the available options. In the example development shown in Figure 6.1, the development being created in the design planner, from a masterplan, contains roads (black lines) with buildings (red, pink, purple, khaki) a grass recreational area (light green), trees (grey circles) and a water feature. Each of the components in the development can be identified using the key at the right hand side. The "view" toolbar allows the user to zoom in or out from a particular part of the development, allowing the user to do detailed work such as adding trees or to create a larger development plan by adding roads or buildings. The "grid" toolbar helps in the process of placing components by providing the user with a customisable overlay which the components will align to if desired. The "Date Selector" allows the user to view the plan at any date during the life time of the development, allowing the user to create changes to the development which will only be enacted at a specific date. Right clicking on the design planner will bring up a context menu allowing the user to add, remove, move, rotate or arrange depth of each component's representation on the planner. The scenario list contains all the scenarios that have been designed for the current project allowing the user to quickly flip between different designs. The scenario list also provides the user with the ability to copy other scenarios in the project or to load scenarios from another project enabling the user to have a range of scenarios without having to recreate each masterplan from scratch. The "main menu" simply allows the user to save or load entire projects.

When the user loads a project the application will ask for an XML file which details all the possible components for that development. This application parses this file to populate the component key and the "add" section of the context menu within the designer. By editing this file the user is able to change the available buildings for a development. All the possible components of a development can be stored within the application allowing the components to be updated or changed at any time. The components of the development can be imported from architectural designs allowing the 3D scenarios to be created quickly and easily from already existing architects' or planners' models. The user is able to include multiple 3D models for each building, representing different options, e.g. building material or external rendering, for that building. Any data, such as the use of the building or the NCM report score, which are to be used by the sustainability model can also be imported for each option for each building.

When the 3D models are first loaded by the designer, the application identifies the footprint of the model using a convex hull algorithm. The designer then displays the 2D footprint of each 3D model added to the development on the design screen. This allows the user to easily build up a complete 2D plan of the proposed development (Figure 6.1). Each component model in the development is stored in an object that contains all its positional and orientation data for both the 2D plan and the 3D virtual world. This means that repositioning a building on the design screen simultaneously updates its position in the virtual world. Figure 6.2 shows an example of this process where a user has both the scenario design screen and the 3D visualisation screen open and is investigating changing the positions of a building and an area of green space.

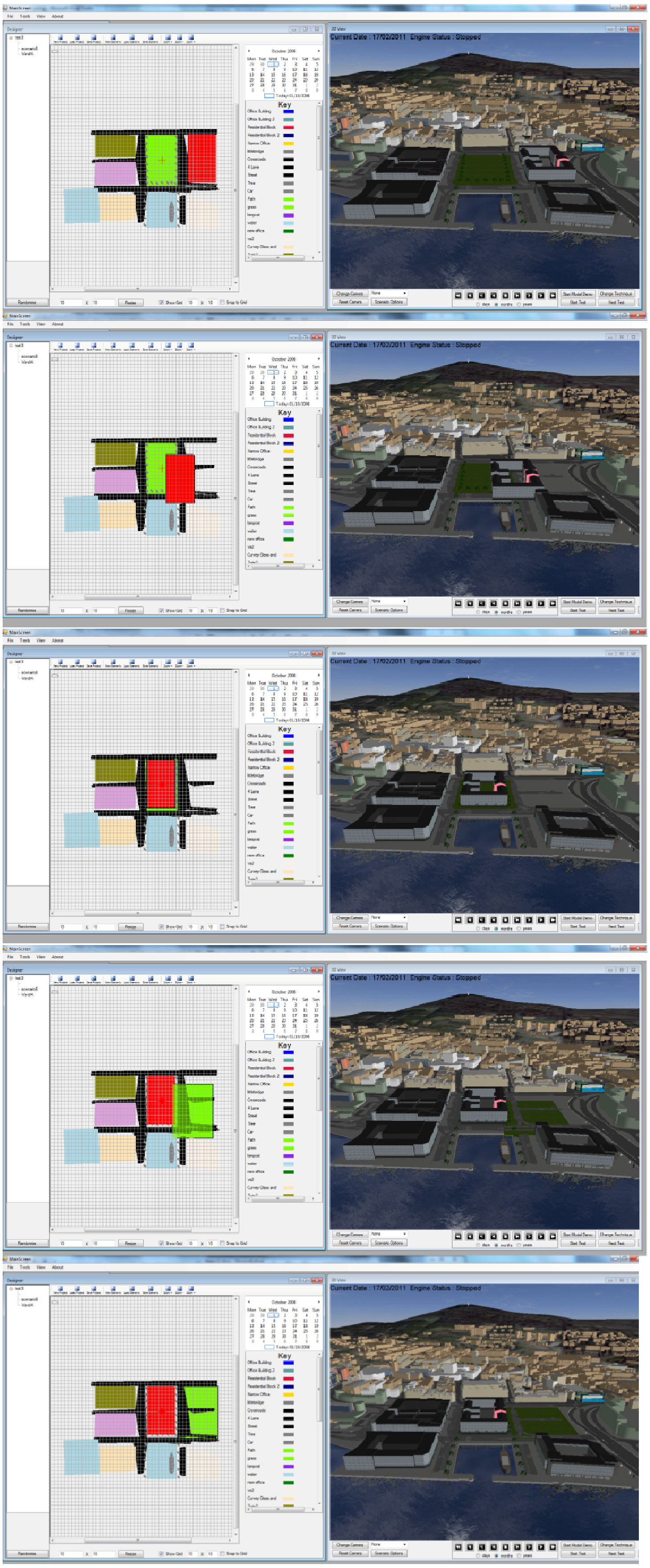


Figure 6.2 Simultaneous link between scenario designer and 3D visualisation

Each of the component objects inherits from a common parent object, which allows all the components to be treated the same by the scenario designer and the renderer that draws them in the 3D visualisation, but separately by the modelling component which will use different calculation depending on what type of component is being modelled. This inheritance structure is shown in Figure 6.3.

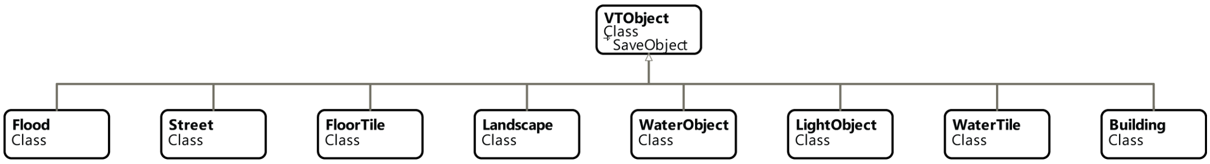


Figure 6.3 Inheritance in development component objects

The user can save the individual scenario or whole project at any time and the application will use binary serialisation to store the components attributes, positions and orientations in packaged files, so that once a design is created the same design can be easily ported to another location running the application.

6.2 Scenario Data

Values for the sustainability indicators used by the sub-system models to determine the sustainability of the structure can also be added or amended using the design interface. The user can double click on any structure in the scenario to bring up a dialogue to display the buildings property's, within which the data used by the sustainability model may be changed. The property dialogues also allow the user to set temporal data such as when the component will be built or how long a site preparation phase is needed. The component objects in which the data is stored allows the scenario designer to show the correct property dialogue for the selected component. Figures 6.4 & 6.5 show the different property dialogues for a street and a building. As can be seen the components have some similar options, such as build & demolish date but also specialised options such as building type or traffic density which are particular to that type of component. The building properties dialogue allows the user to choose between the different options for that building as imported to the system, which allows different building options to be visualised extremely quickly by simply switching between the differing options using the drop down boxes.

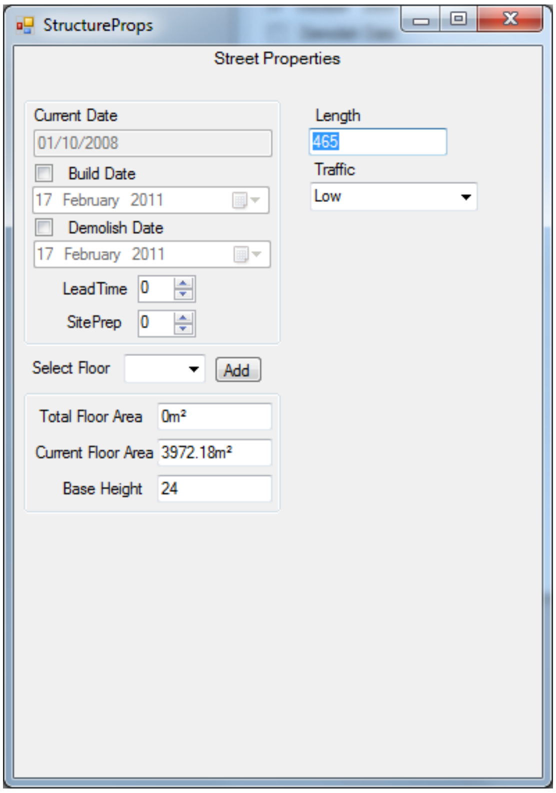


Figure 6.4 Properties for a street component

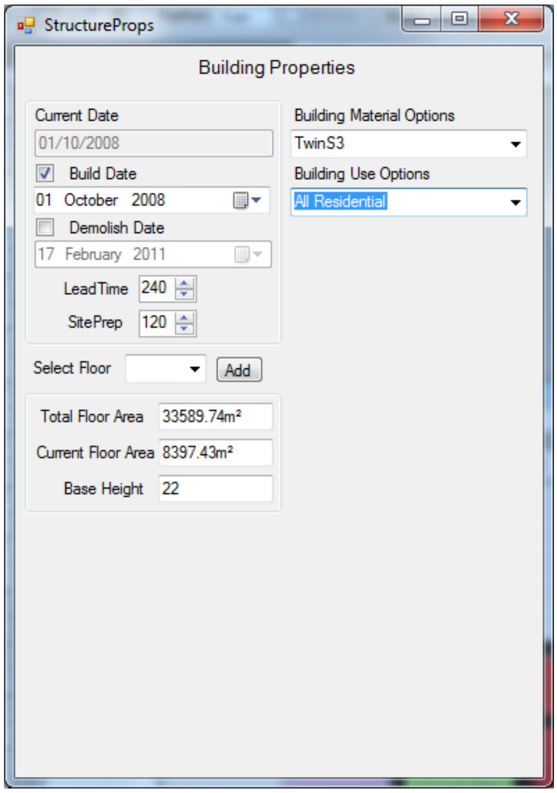


Figure 6.5 Properties for a building

Again all the data for the individual components are stored in the component object allowing the user to change the design at any time, with any changes made being reflected immediately in both the underlying computational model and the 3D visualisation. This allows the user to determine the effect of the change they have made and thus the consequences of this decision in different scenarios.

6.3 Summary

Chapter 6 describes how S-City VT allows the creation of unlimited scenarios based on the development being investigated. As has been described through the creation of the scenarios and the manipulation of the components, the indicator values used by the modelling component (Chapter 4) will also change. This change will be reflected in the visualisation techniques detailed in Chapter 8. Chapter 7 describes how a 3D representation of the scenario is created so the physical appearance of the scenarios can be investigated.

Chapter 7 Creation of 3D Rendering Framework

7.1 Development of the 3D Visualisation Component

The 3D Visualisation component is designed to allow the users to view both the data being produced by the indicator modelling and multi-criteria analysis to determine the sustainability impact and also the visual impact of their decisions. As has already been discussed, it is extremely important that there is a great amount of flexibility in the visualisation component, both to show the physical appearance and in demonstrating the underlying sustainability data. To enable this flexibility it is important to have an extremely close link between the underlying sustainability modelling component, the scenario design component and the visualisation component to allow the results of the sustainability models and the scenario designs to be displayed seamlessly on the 3D virtual development.

Given S-City VT will have a strong visual component, custom visualisation techniques and computational models C# and XNA will be the tools used to develop the S-City VT DST. The Microsoft XNA framework facilitates rapid game engine production by providing a set of tools utilising a managed runtime environment. XNA essentially relieves much of the repetitive nature of creating a custom engine by providing basic methods and allowing easier access to the rendering and processing ability of a computers graphics hardware. Development of the visualisation component in XNA will allow the indicator models, implemented in C#, to be easily linked into the visualisation.

7.2 User Interface Development

From the literature reviewed, it is clear that for the tool to be effectively used by the decision makers and stakeholders it is important that it is easy to use. To keep the user interface simple it should use components that the user can recognise as being the same or similar to components they have used before, e.g. user interface controls common on the desktop environment such as labels, buttons, menus etc. The XNA framework was created as a development tool for games and as such was not designed to use the common desktop interface components but to utilise HUDs as described in Chapter 2. To make the visualisation tool resemble a common desktop application but to also include the game engine component which will drive the visualisation allowing incorporation of visualisation techniques through the use of the programmable pipeline and the creation of custom pixel and vertex shaders, it was necessary to develop a custom component which would allow the 3D graphic rendering (developed using the XNA framework) to be coupled with the common desktop components (provided by the C# Winforms library). The structure of the 3D view component of the application is shown in Figure 7.1.

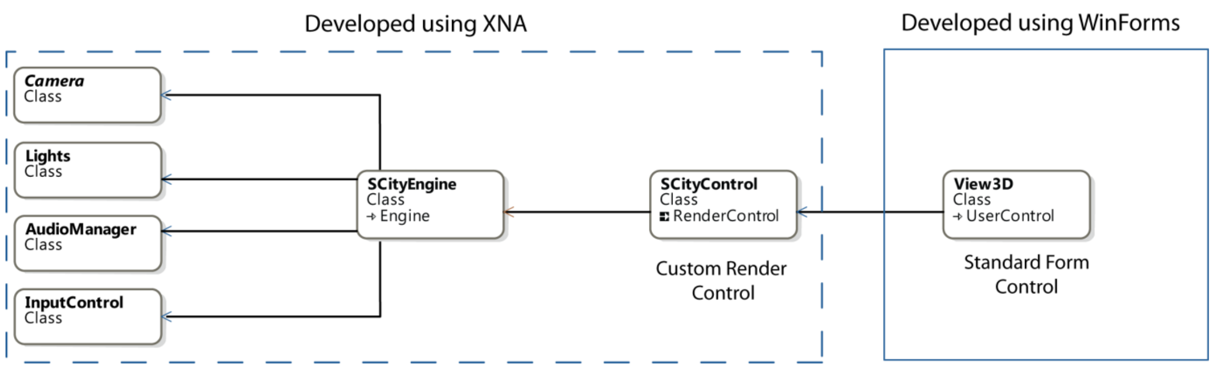


Figure 7.1 Class diagram showing S-City VT Winforms & XNA architecture

The custom render control and the engine developed using XNA, handles all the rendering of the 3D environment onto a single component which can be added to a standard windows form developed in C# using the WinForms Library, along with the other standard components which the user will be familiar with. This process allows the user to interact with the 3D environment using the mouse controls, similar to a game control system, but change the available options using standard onscreen components, resembling a standard windowed application.

7.3 Early Prototypes

Figures 7.2 & 7.3 show an early prototype of the 3D visualisation tool. The prototype was designed to test the interactions between the scenario designer and the visualisation. The development has been populated with simple buildings with different appearances and uses.

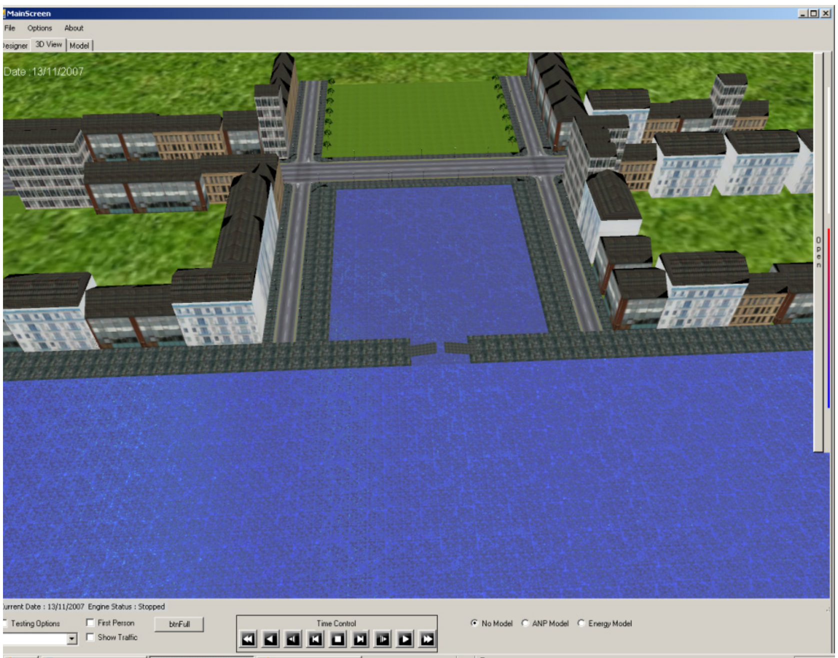


Figure 7.2 Early prototype of S-City VT

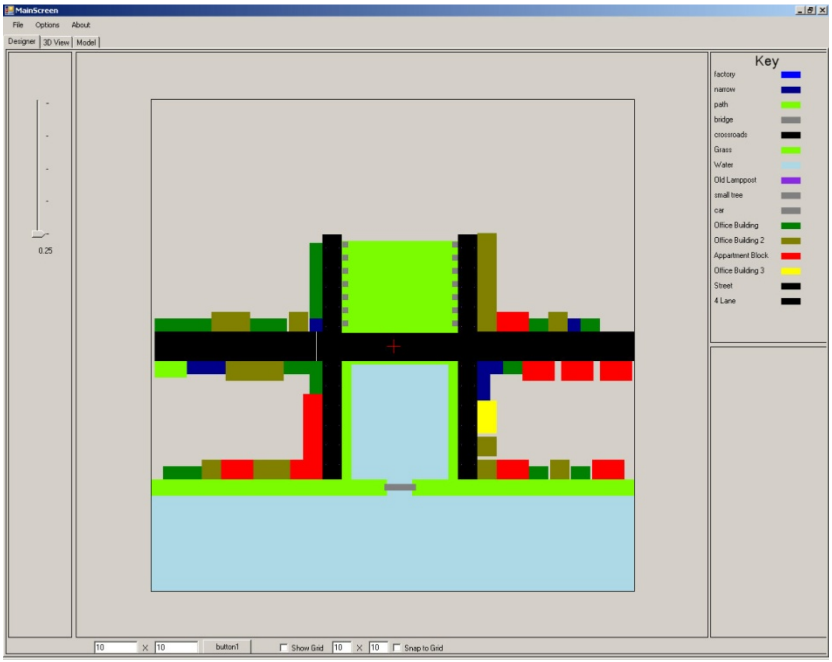


Figure 7.3 Scenario designer for development shown in Figure 7.2

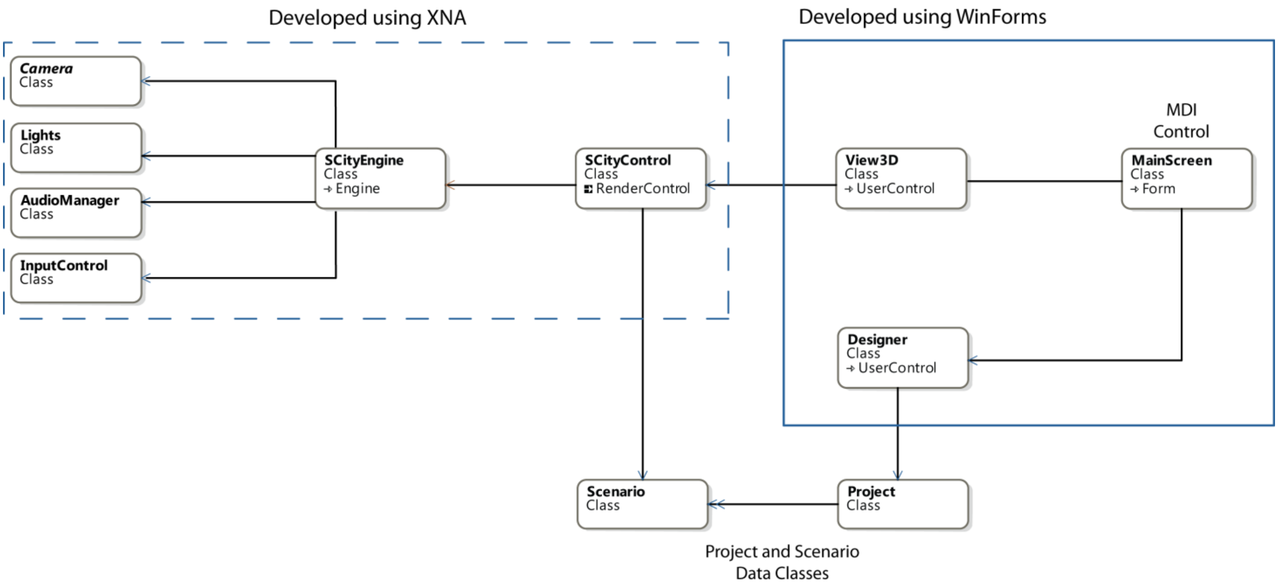


Figure 7.4 Overview of links between Scenario Designer and 3D component

As can been seen in Figure 7.4, a single multi-document interface (MDI) called "MainScreen" was created to contain both the 3D (3D View) and Scenario Designer (Designer) components. The "MainScreen" forms the first point of contact with the user; all the functions of the application will be available from here, allowing the user to quickly find the function they are wishing to use. A MDI was used to allow both components to be seen individually or together, allowing the user to investigate how changes in the design are shown on the visualisation immediately and not be required to flip between views. The “Project” and “Scenario” data classes allow the “Render Control” to have access to the current project and scenarios being developed in the scenario designer. Each instance of the project class may have a unlimited number of scenarios associated with it, representing the list of possible options for the development under assessment. In turn, each of the scenarios will have a set of buildings, or other components of urban developments with which the scenarios have been designed. Each of these components are stored within a specialised class which will hold all the data spatial information for that component along with the data which is to be used by the sustainability model as shown in Figure 7.5.

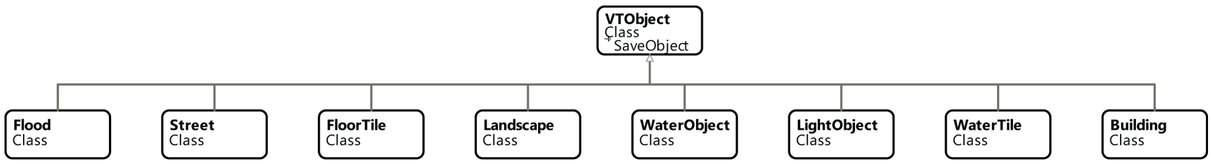


Figure 7.5 Specialised development component objects

Each specialised development component object inherits from a common parent object, allowing all the components to be treated the same by the scenario designer and the renderer but separately by the modelling component which will use different calculations depending on what type of component is being modelled.

7.4 Integration of GIS and 3D view

Traditionally either 2.5D GIS or full 3D models generated from CAD have been used in city modelling. As has already been discussed, existing GIS systems still rely heavily on experts both in the training of the tools and in understanding the forms in which the data are being presented (Shiffer 1998). Using traditional GIS also does not provide a realistic physical representation of the city or development being studied, as being two dimensional it lacks a realistic representation of height and perspective. GIS can, however, provide a better two dimensional depiction of a large area using aerial photographs or detailed maps. CAD systems do enable the creation of 3D models which provide the user with a realistic representation of the buildings and the developments (Al-Kodmany 2002), however CAD systems provide no ability to overlay additional data and provide little context outwith the building or area being studied and do not usually give the users, other than the initial designer, the opportunity to control what viewpoint location or orientation is being used. To increase the potential effectiveness of S-City VT the benefits of GIS and 3D urban models are combined to embed the 3D models in the surrounding landscape, which is characterised by GIS data, to contextualise the urban area that is undergoing sustainability assessment. The 3D models of the building in the area surrounding the waterfront development was produced by Dundee City Council primarily using Google Sketchup, a commonly used drawing application especially in local government. These Sketchup Models were simply converted to a format useable for the 3D visualisation component using the 3D Studio MAX software. The 3D models representing the main waterfront development were also created in 3Ds MAX from artists' representations of the possible buildings. By combining all these components together the visualisation becomes instantly recognisable as the City of Dundee. This ability to visualise part of the city that is undergoing the development or regeneration within the wider city context is likely to improve engagement with the communication tool and bring a greater level of involvement from all participants in the planning process (Levy 1995); the results of adding the surrounding buildings and city context to the visualisation tool are shown in Figure 7.6.

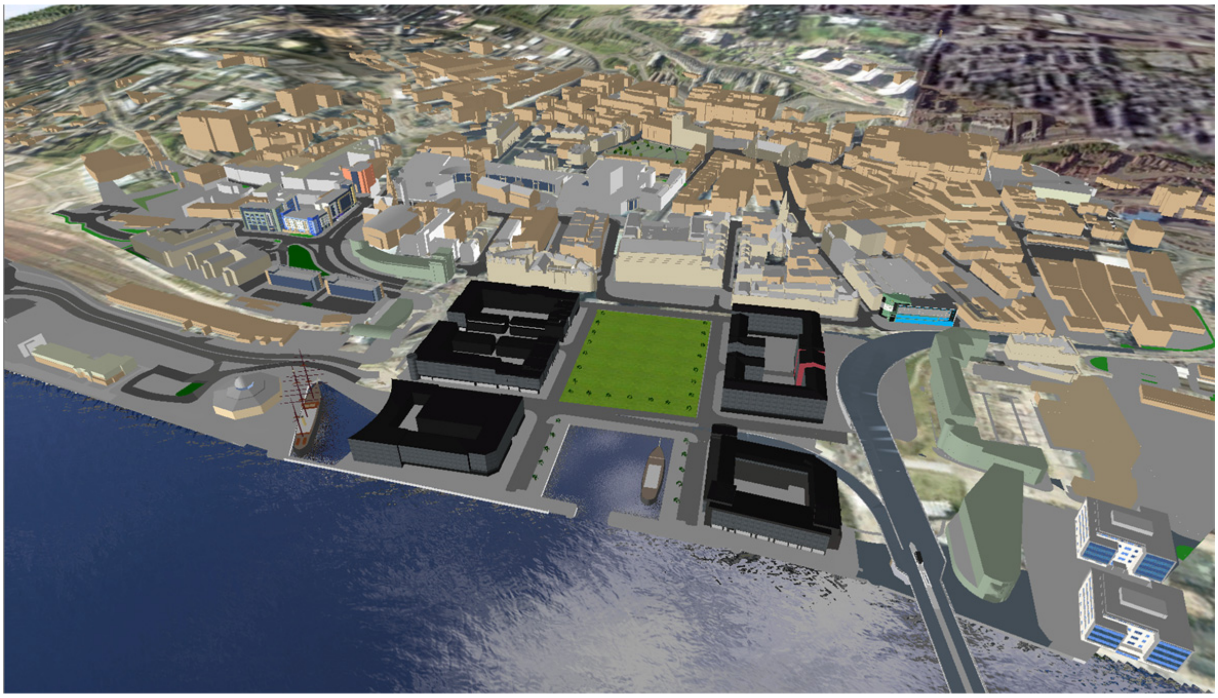


Figure 7.6 3D representation of proposed development within the city-wide context.

7.5 Interactive Camera Control in the 3D environment

The engine allows the user to have interactive control enabling the user to view the proposed development from any conceivable viewpoint. This allows the user to become fully immersed in the proposed development, to a much greater degree than 2D plans, GIS, or rendered 3D stills. The ability to view the development from any viewpoint allows the stakeholder to view the development in ways that they feel would affect them, not a fixed viewpoint provided by someone else. Changing the viewpoint and angles also allows the user to get a view on the height, scale and perspective of buildings at the level they would be looking at them in real life; this range of views is shown in Figure 7.7.

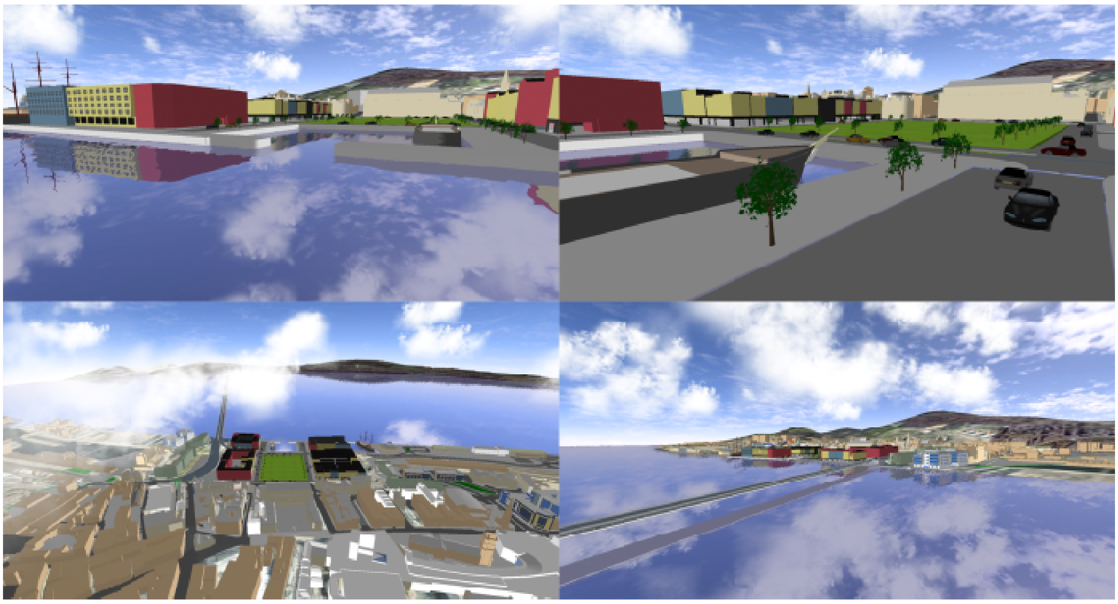


Figure 7.7 Range of available views in S-City VT

The use of 3D environments in this way also enables some of the user's cognitive navigation and visual perception processing to be performed on a sub-conscious level as they will already have developed this ability through real world activities, such as walking through a city, with little conscious thought (Charters et al. 2002a) which allows the user, once they are familiar with the view and controls of the system to concentrate more fully on the decision being made. The controls for the 3D visualisation (mouse and the WASD keys) have been made deliberately simple using only 4 keys so they are easy to pick up and were chosen due to their wide spread use in computer games featuring virtual environments. Additional keyboard controls have been added for those who do not wish to or cannot use a mouse; view controls are highlighted below in Figure 7.8.

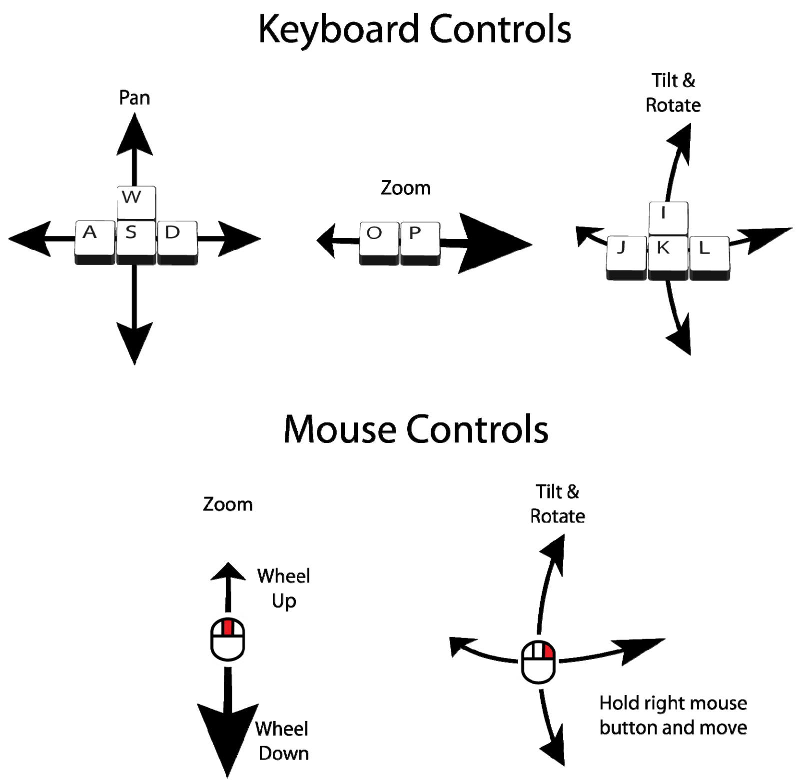


Figure 7.8 View controls for S-City VT

It may be the case that some users who are unfamiliar with computer controls may wish to control the application in a more intuitive manner. To allow this the application utilises a freely available C# library (WiiMoteLib) which allows the movement from the Nintendo Wii remote to be read from any C# application. S-City

VT translates the movement data from the Wii remote in a way which allows the navigation of the environment and some of the scenario options to be controlled.

7.6 Scenario comparison

The visualisation component of the application provides a spit screen view to facilitate investigation of contrasting planning scenarios such as the effect of building attributes on urban performance (Figure 7.9). The sustainability models of all the scenarios in the scenario designer are run simultaneously; the spilt screen view allows the user to pick any two of these scenarios enabling the users to stop and compare the scenarios at any time point. Each of the viewports of the split screen interface is controlled by the same user input, so the viewpoint location and orientation of the user's camera remain the same for both views. By coupling the viewports in this way the user can investigate the visual impact of each scenario from the same location and perspective. The scenarios may be changed at anytime thus allowing the identification of the best scenario from several possibilities.

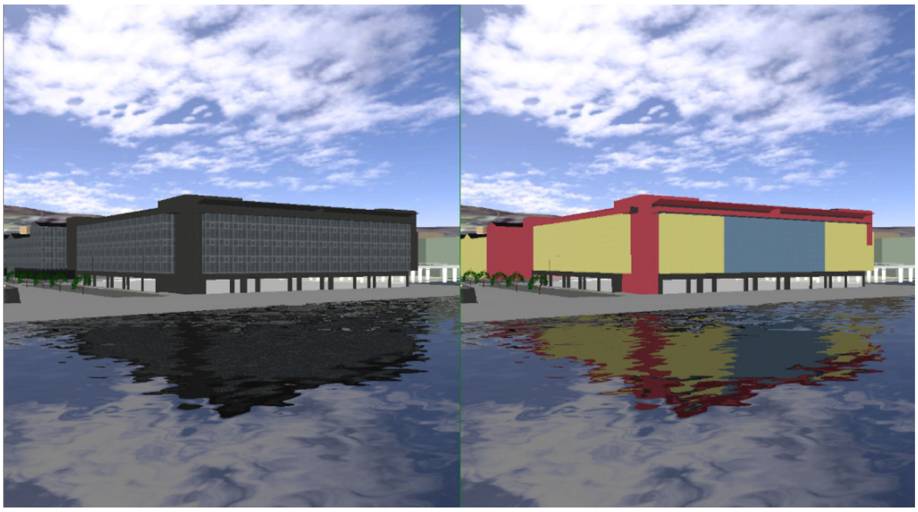


Figure 7.9 Split screen comparison, here the comparison is based on preference of building materials.

7.7 Immersion

While the application can be used on consumer desktop and laptop machines, it has also been developed to allow its use in both fully immersive and partly-immersive environments. Through the use of a stereoscopic projection environment, the user can become fully immersed in the proposed development. The stereo vision allows the user to feel as if they are standing in the environment, as seen in Figure 7.10, and that the simulation is coming to life around them, isolating them from the real environment (Okeil 2010).

Figure 7.10 Application on stereo projection screen (left) and audience viewing (right)

However, as the application is designed to be used for sustainability assessment and planning it would not always be possible to have all the stakeholders visit the stereoscopic projection environment. To allow a wider range of users to experience the proposed development in stereovision, the application can also utilise a portable Stereo 3D monitor. This allows the application to be executed on a laptop connected to the 3D monitor which, like a normal computer display, will not fully immerse the user but will allow the user to better perceive depth and perspective with the aid of stereovision.

As has been mentioned in Chapter 7, S-City VT includes the possibility of interfacing with the Nintendo Wii remote, allowing a more intuitive control system for navigation of the virtual environment presented in the visualisation tool. When this control system is combined with viewing the virtual environment using stereo projection, either on a large screen or 3D monitor, it has the advantage of not only providing an easier control system, but also in attracting a wider range of users, such as children and young adults who are more familiar with using this type of control system in computer games and viewing films using stereovision. Feedback from early user trials with visitors to the Sensations Science Centre in Dundee, suggested that the attraction of visualisation would be greatly enhanced if there was a character in the environment that the user could control. The Dundee waterfront location, combined with the freedom of view the visualisation tool provides, led to the addition of an animated mechanical seagull as an interactive character. The user is able to control the seagull, which utilises a slightly different camera mode to simulate flight, with the Wii remote to enable then to fly through the virtual environment. From observation of the users at subsequent public events it was clear that both younger and older people were attracted by the ability to fly through their city, which also meant that they were much more inclined to play with the other features, like scenario design and more likely to take an interest when the data views were in place.

7.8 Experiment to determine viability of virtual environment

While it has already been suggested in previous research (Kapelan et al. 2005a; Danahy et al. 1999; Charters et al. 2002b; Levy 1995) that using 3D visualisation to allow stakeholder to see a development may aid the stakeholder in making decisions, it is not clear whether the stakeholders would have different opinions than they would in real life when shown a virtual representation. Appleton (2003), Lange (2005) and Davies & Laing (2002) have all shown that the realism of any visualisation of the real world is important in engaging the stakeholders. Lange (2005) in particular shows that the representation of the real world must be fair to the stakeholders and any visualisation should not, either intentionally or unintentionally, mislead the users or influence their choice of scenario through the use of a particular abstraction or visualisation technique. If users have vastly different opinions of particular building types when shown real and virtual representations, the visualisation tool may not be viable in expressing physical appearance. To determine the viability of the virtual environment an experiment was conducted to determine if a user's preference for specific building types was affected by seeing the building in a real or virtual setting. If the preferences are the same it can be surmised that the virtual world is representative enough so as not to affect the user's preference.

Photographs of real buildings and virtual representations were used to analyse people's preferences for different building types and to determine if the prototype provided a viable representation of a development. The participants were given a series of questions, each question contained two images, one of a predominately glass building and one of a predominately brick building. In the first set of questions both images were photographs of real buildings (Figure 7.11), in the second set of questions both images were virtual representations (Figure 7.12).

Figure 7.11 Example representation of real buildings used in building appearance survey

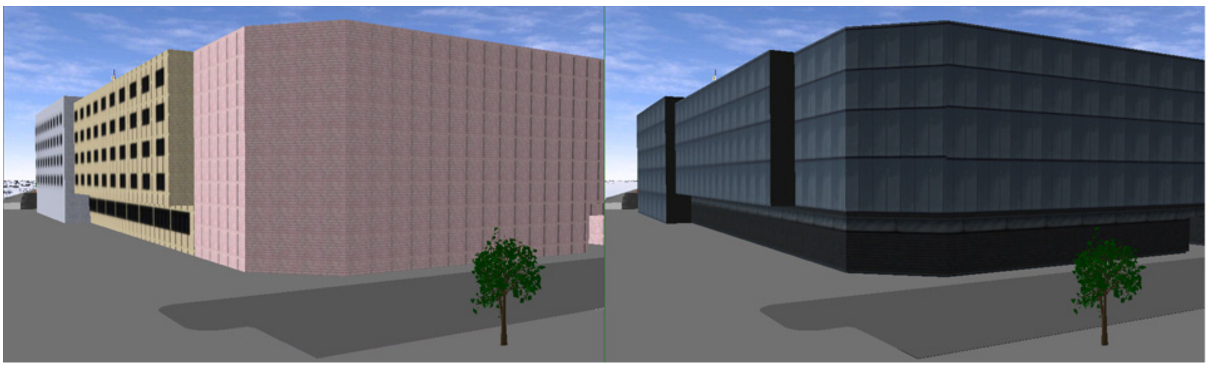


Figure 7.12 Example representation of virtual buildings used in building appearance survey

Table 7.1 Descriptive statistics

	Virtual Q1	Virtual Q2	Virtual Q3	Virtual Q4	Virtual Q5	Real Q1	Real Q2	Real Q3	Real Q4	Real Q5	Real Q6	Real Q7
Number	106	106	106	106	106	106	106	106	106	106	106	106
Mean	2.95	2.90	3.42	3.12	3.53	3.30	2.67	3.44	2.70	2.82	2.86	3.35
Median	2.50	2.50	4.00	4.00	4.00	4.00	2.00	4.00	2.00	2.00	2.50	4.00
Mode	2	4	4	4	4	4	2	4	2	2	2	4
Maximum	5	5	5	5	5	5	5	5	5	5	5	5
Minimum	1	1	1	1	1	1	1	1	1	1	1	1
Std. Deviation	1.533	1.454	1.379	1.446	1.388	1.462	1.350	1.295	1.500	1.308	1.245	1.273
Skewness	.048	.032	-.475	-.141	-.712	-.317	.459	-.422	.394	.235	.123	-.318
Kurtosis	-1.585	-1.523	-1.133	-1.465	-.906	-1.405	-1.115	-1.035	-1.381	-1.202	-1.264	-1.076

The participants were asked, using a Likert scale ranging from 1 to 5 to rate their preference for one of the buildings they were being shown, with 1 and 2 defining a strong and slight preference for brick buildings respectively, 3 defining no preference and 3 and 5 defining slight and strong preference for glass buildings respectively. As can be seen from the descriptive statistics (Table 7.1), the mean for each question is generally just above or below the centre of the scale, this suggests that there were no questions which provoked a particularly strong preference for either glass or brick buildings. The relatively small standard deviations, low skewness and platykurtic kurtosis characteristics for each question also support this.

Determining if virtual or real building representations affected the participant's preferences.

To determine if the participants had significantly different views if the buildings represented were real or virtual, the means of the virtual and real building questions were treated as two independent samples in a Mann-Whitney and a Kolmorgorov-Smirnov non-parametric significance test.

<u>Null Hypothesis: Participants will show the same preference for brick or glass buildings regardless if the building representation is real or virtual.</u>

Table 7.2 Significance tests on building appearance survey

Mann-Whitney

	mean
Mann-Whitney U	10.000
Wilcoxon W	38.000
Z	-1.218
Asymp. Sig. (2-tailed)	.223
Exact Sig. [2*(1-tailed Sig.)]	**.268[a]**

a. Not corrected for ties.
b. Grouping Variable: visualisation type

Kolmogorov-Smirnov

Kolmogorov-Smirnov		mean
Most Extreme Differences	Absolute	.571
	Positive	.571
	Negative	-.029
Kolmogorov-Smirnov Z		.976
Asymp. Sig. (2-tailed)		.297

a. Grouping Variable: type

Both tests gave results above the 5% confidence level, as shown in Table 7.2, using the null hypothesis, that real or virtual buildings will have no affect on the participant's preference for brick or glass buildings. These results suggest that there is not enough evidence to reject the null hypothesis and therefore, for this example, there was no significant difference between the participant's preferences when real or virtual representations for the buildings were used. This supports the researcher's view that S-City VT provided a viable representation of the buildings.

Determining if real or virtual buildings affected the strength of the participant's preferences.

While there was no significant difference found between the preferences or the use of virtual and real building representations, there has been previous research which suggests that virtual representations can provoke a stronger response as photorealistic building representations look finalised to the participant. In this case the number of slight preference, strong preference and no preference results were collated; this would give an indication of the strength of responses (Table 7.3). The numbers of responses were for the real and virtual building representations were treated as two independent samples for a Mann-Whitney test, with the null hypothesis that there will be no significant difference between the slight, strong and no preference numbers between real and virtual building representations (Table 7.4).

Null Hypothesis: There will be no significant difference between the number of participants showing slight, strong and no preference between real and virtual building representations.

Table 7.3 Preferences for glass and brick buildings in virtual and real representations

	type	Number	Mean Rank	Sum of Ranks
No Preference	virtual	5	3.90	19.50
	real	7	8.36	58.50
Slight preference	virtual	5	6.70	33.50
	real	7	6.36	44.50
Strong preference	virtual	5	8.30	41.50
	real	7	5.21	36.50

Table 7.4 Non –Parametric significance tests for building comparison survey

	No-preference	Slight preference	Strong preference
Mann-Whitney U	4.500	16.500	8.500
Wilcoxon W	19.500	44.500	36.500
Z	-2.122	-.164	-1.477
Asymp. Sig. (2-tailed)	.034	.870	.140
Exact Sig. [2*(1-tailed Sig.)]	**.030[a]**	**.876[a]**	**.149[a]**

a. Not corrected for ties.

b. Grouping Variable: type

The results for the slight and strong preference numbers, 0.876 and 0.149 show that for these two variables the null hypothesis cannot be rejected, however the 0.03 results for the no preference numbers is within the 5% confidence level. The result for the no preference variable suggests that there is a difference between the number of people who will have no preference when asked to choose between real buildings and the number who will have no preference when asked to choose between virtual buildings.

This result seems to show that that virtual, non-photorealistic, representations provoke a stronger response from stakeholders and so could aid in facilitating discussion about the choices provided.

7.9 Summary

Chapter 7 describes how the S-City VT framework has been developed to combine 3D rendering engine and game like interactivity with scenario design to represent the physical appearance of the environment. The experiment performed to determine if peoples' preferences changed when viewing a realistic representation of a development show that the virtual representation produced by S-City VT did not produce different building preferences within the participants asked. There was however, some evidence to suggest that the virtual representation provoked a stronger response and that this may aid S-City VT provoke more discussion during the decisions being made. The next chapter describes how the 3D rendering component combined with novel visualisation techniques allow the presentation of the sustainability indices produced by the modelling (Chapter 4) and ANP components (Chapter 5).

Chapter 8 Visualisation of Sustainability Data

The results from the viability experiments reported in the previous chapter seem to show that the 3D virtual environment created in S-City VT does adequately represent the real physical environment. The next step in the development of the tool was to implement the ability to project the results of the sustainability models and the multi-criteria analysis onto the 3D environment.

This process required combining the visualisation tool, the sustainability models and the scenario designer as shown in the class diagram in Figure 8.1.

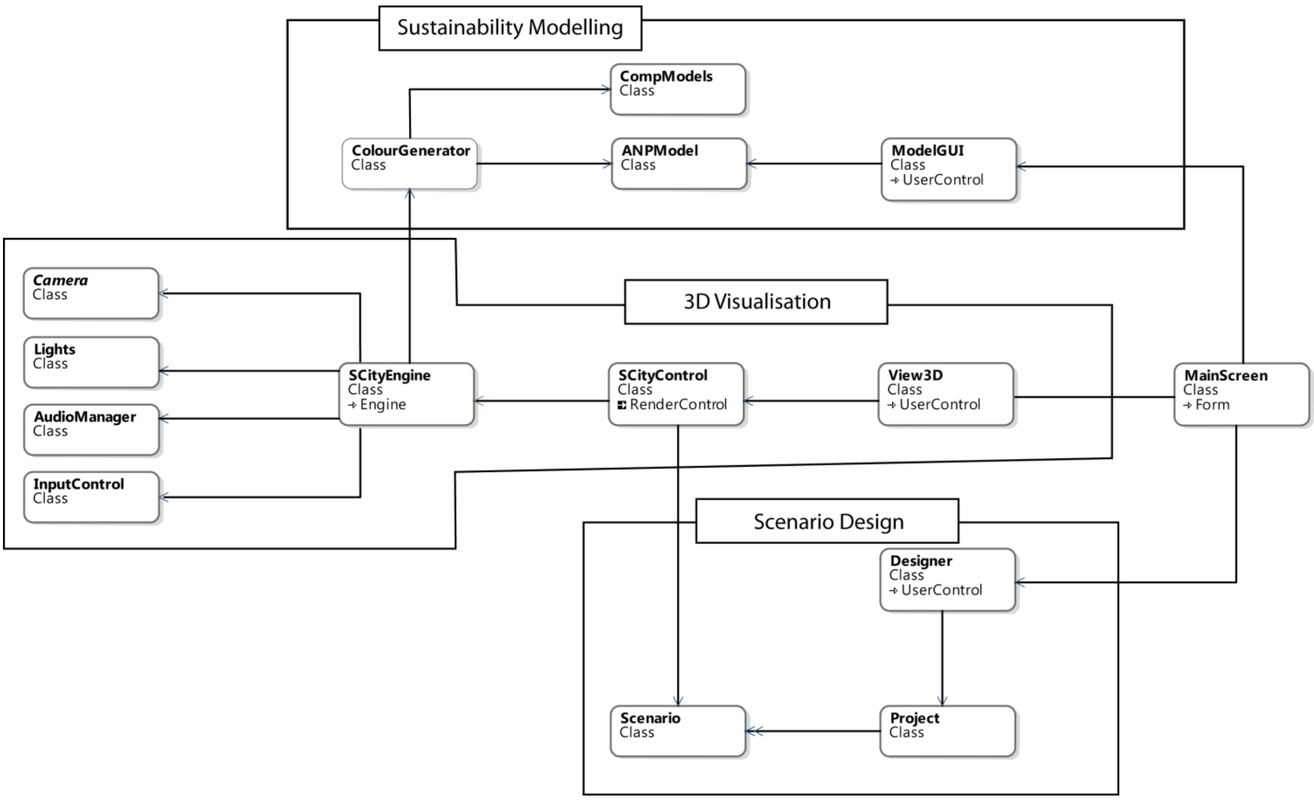


Figure 8.1 Class diagram showing integration of 3 main components of S-City VT

The results of the computational model (represented by the CompModels class in Figure 8.1) provide a value for each indicator for each component of the development, i.e. each floor of a building or each street. The maximum and minimum results for each subsystem are obtained across all the scenarios being studied by performing a calibration run prior to the actual assessment. These are used to perform linear maximum-minimum normalisation on the results of each subsystem to give a value between 0 and 100.

To determine a sustainability measure for a specific component at a given time, in the development the normalised indicator values, obtained from the sub system models are multiplied by the weights/priorities provided by the multi-criteria analysis, ANP, model (represented by ANPModel class in Figure 8.1). This gives a quantitative measure of sustainability for each building. However, S-City VT does not provide the user with a definite measure of sustainability, but allows the user to compare the relative sustainability of alternate decisions represented by the possible scenarios created in the scenario designer.

It has been shown (Nakakoji et al. 2001) that by interacting with animated visualisations to identify prominent data changes and investigating values at particular points in time, users gain a feeling of immersion and are able to intuitively understand the data being presented. S-City VT enables this by using the virtual environment to display the results of the underlying computational models demonstrating the sustainability of the proposed development or scenario and its constituent components. The prototype tool displays the information using a number of different techniques, reflecting the different preferences, ability and experience of the wide array of stakeholders, who it is envisaged will use the tool. The visualisation techniques employ pixel and vertex shaders for efficient rendering of data. The pixel shaders control how each pixel of the building mesh is drawn allowing the building textures to be changed quickly on the graphics processing unit (GPU) removing the need to perform computationally intensive texture manipulation on the CPU (Purcell et al.

2002) . The Colour Generator class in Figure 8.1 performs the conversion of the sustainability indexes obtained from the sub-models into specific colours which can be used in the visualisation techniques described below.

8.1 Blending

The blending technique, as shown in Figure 8.2, simply takes all the normalised sustainability measures for each indicator, calculated by the sub-models and aggregates them into a single sustainability index using the weights provided by the ANP analysis. This value is then mapped to a single colour scale with 0 representing the lowest sustainability index and 100 representing the highest. Using the hot-cold scale demonstrated in Figure 8.2, a building or floor with high relative sustainability would appear blue while a building with low sustainability would appear red. This method gives a single indicator of sustainability and provides the easiest way of comparing the relative sustainability of different options or scenarios.

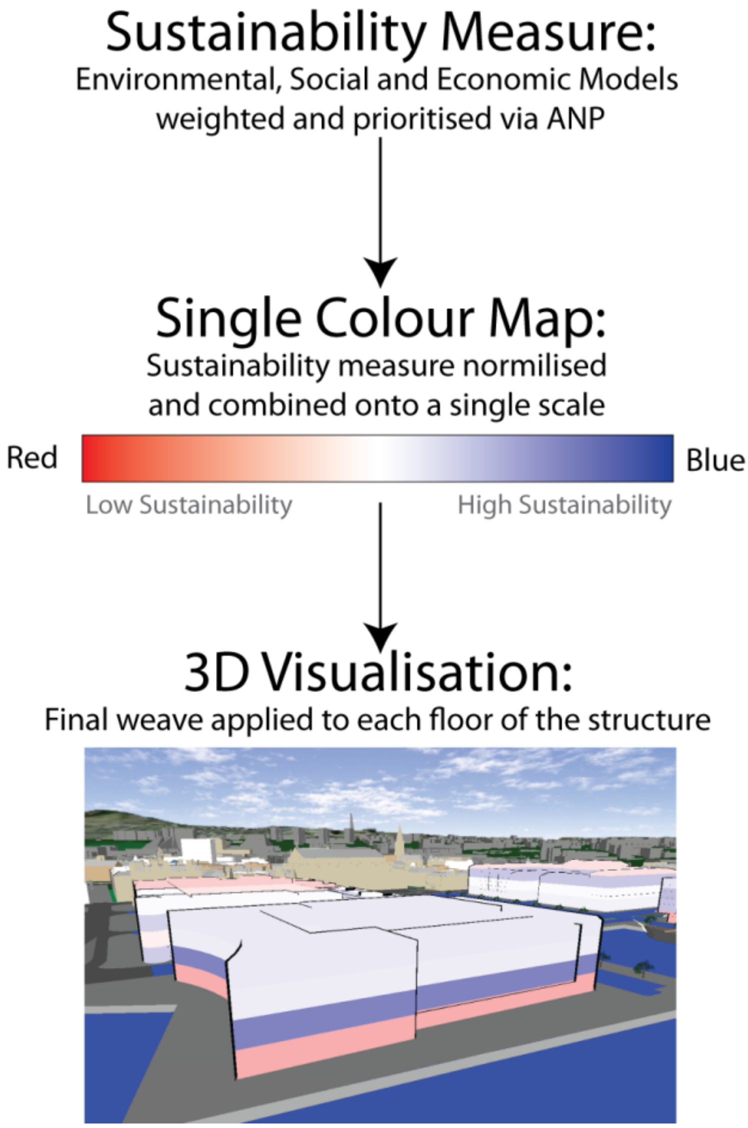


Figure 8.2 Steps in the Blending technique

Usually to render a 3D model the 3D engine passes a mesh which contains all the locations and orientations of the triangles which define the shape of the model, along with any textures which will define the outward appearance to the graphics hardware. For the blending technique, pixel shaders are used to alter this process so that instead of the buildings normal texture the results of the sustainability model are shown. The first implementation of the blending technique used the sustainability models to generate a colour for each building floor; once the colours have been generated, a simple texture was created containing a one pixel square for each floor. This texture was then passed to the Pixel Shader. However there was slight performance degradation (i.e a drop in framerate) due to the creation of a new texture for each building for each render frame. This performance degradation, while not evident when rendering a simple building would have a much bigger impact when modelling a whole development. To overcome this an array with each element containing a separate colour for each floor is created, this array is then passed to the pixel shader. The pixel shader, which is processed on the graphics hardware, uses the current pixels height position in the building to determine the correct the colour, from the generated array, that should be applied. This process is shown in Figure 8.3.

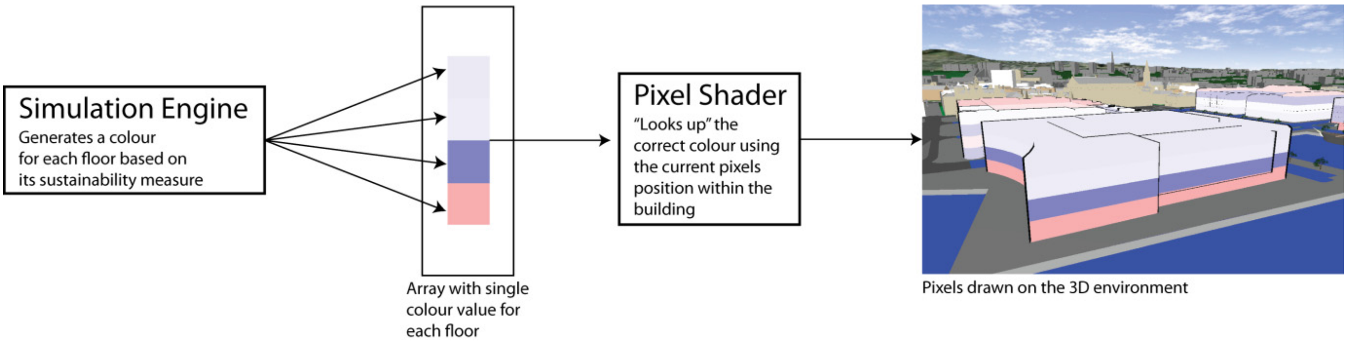


Figure 8.3 The Blending technique pixel shader

Whilst the example here shows a colour scale from red to blue, it is recognised that some stakeholders may prefer to make their decision based on a different scale, which could be due to visual problems such as colour blindness, environmental conditions such as lighting or simply personal preference. Because of this the colour scale used can be selected from a number of colour scales known for their discriminating abilities and commonly used in medical applications (Levkowitz & Herman 1992). These include the heated object, magenta, local optimised, and spectral, as shown in Table 8.1.

Table 8.1 Available colour scales used by the Blending Technique

	Red White Blue Scale	
low		high
	Heated Object Scale	
low		high
	Magenta Scale	
low		high
	Optimised Colour Scale (OCS)	
low		high
	Spectral Scale	
low		high
	Grey Scale	
low		high

8.2 Weaving

Whilst the blending technique combines the indicator values, the weaving technique (

Figure 8.4) attempts to preserve some of the underlying information so that the user can still identify which indicators or clusters are causing the greatest effect (negative or positive) on the sustainability of the building. The colour weaving technique (Hagh-Shenas et al. 2007) uses a different colour scale for each indicator (Figure 8.4) to attempt to preserve this information, again 0 represents the lowest sustainability index and 100 the highest. The colours from each scale are then randomly weaved into a patchwork-like texture which is applied to each floor of the building. The size of the squares or patches in the weave can also be changed depending on the user's preferences. A small patch size will give an overall representation of the sustainability, with darker shades representing low sustainability and lighter shades representing higher sustainability. A larger patch size will allow users to identify quickly which colours stand out the most, and therefore which indicators are having the greatest effect. The random pattern used will be the same scale across all the buildings in a development and across all the scenarios being assessed. This means that the amount of data which can be displayed is not dependant on the size of the building or area being assessed.

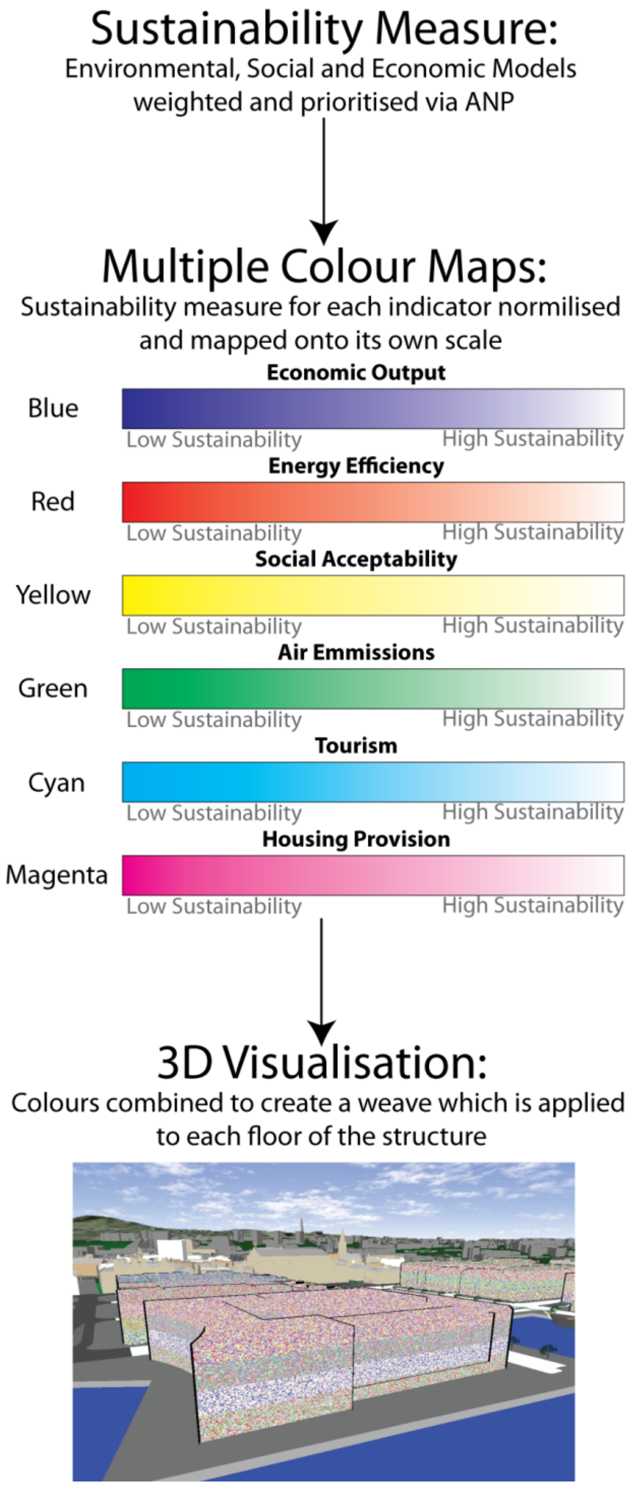


Figure 8.4 Steps involved in the colour weaving technique

As with the blending technique, the weaving technique creates an array containing the colours that will be used to represent the sustainability of the building. However, as the separate indicators values must be preserved, this array must also contain the colours for each indicator for every floor of the building. This requires the generated array size to be much larger, i.e. equal to the number of indicators by the number of floors in the building; this is still much smaller and quicker to process than creating a new texture for every render frame.

The weave technique also needs a random noise texture, allowing for the random selection of the indicator colours, to be generated. The noise texture is created as a large texture populated with different alpha channel (transparency) values. Each alpha value represents a single indicator, distributed randomly over the texture. The pixel shader uses current pixels height position to select the correct floor and the alpha value in the noise texture to select the correct indicator and thus the colour for the pixel (Figure 8.5).

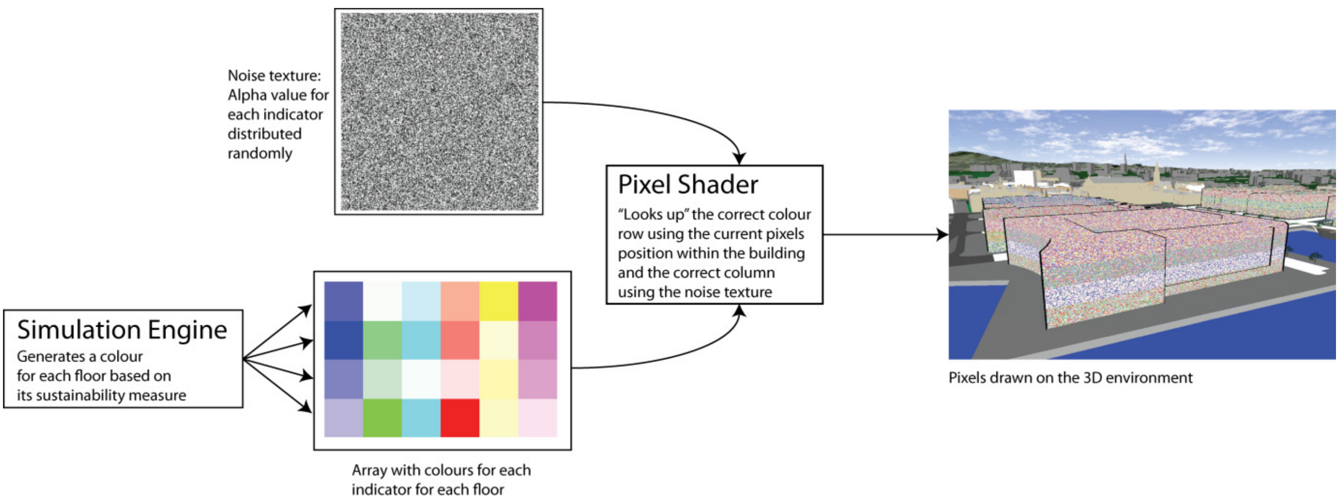


Figure 8.5 The weaving pixel shader

One aspect of the implementation of both the weaving and the blending technique is that it is important that the colours being used are not affected by the underlying textures but that the building still remains recognisable for the user. As Lange (2005) suggests, any abstraction must still be recognisable by the user. Initially the presentation of the data was achieved by overlying the sustainability colour maps over the buildings by altering the buildings transparency, the effects of these different approaches can be seen in Figure 8.6.

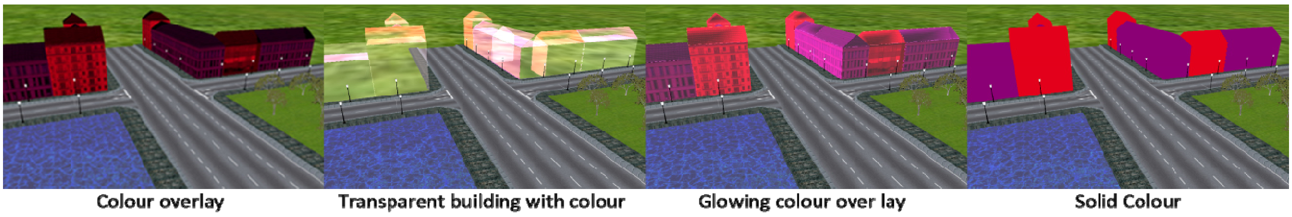


Figure 8.6 Early version of S-City VT showing different approaches to overlaying sustainability data on the virtual environment.

It was clear, however, that this approach would lead to the sustainability colour maps being affected by the underlying building texture, and that the only viable option would be to show the results of the sustainability models using solid colour. Using solid colours to display the sustainability information does diminish the user's ability to discriminate between the elements of the virtual environment. As the solid colour image shows in Figure 8.6 it is extremely difficult to identify the boundaries between the buildings. One possible solution to this would be to make the outline of each building visible, which was initially implemented using a post process pixel shader which is applied to the user's current view and would outline any edges present. Post process shaders are extremely processor intensive, requiring the whole view to be rendered separately for the shader to be applied, which leads to a substantial drop in frame rate which would be even more noticeable when rendering a larger environment and may not permit changes to be viewed in real time. A much quicker method of displaying an outline was developed using two pixel shader passes to render each building to be outlined twice; the first render pass produces a solid black building with no texture, the second pass renders a slightly smaller version of the same building with the appropriate colour maps applied this gives each building a cartoon like outline. This should allow the user to identify the boundaries of each building.

8.3 Animation

The colour overlays provide a method of displaying the results from the sub-system models. However the use of a game like rendering engine allows us to provide some more metaphorical techniques appropriate to some of the other indicators being modelled. One of the major changes in Dundee waterfront is the introduction of wide, major roads which will carry traffic to and from the Tay Road Bridge. These roads will pass directly above and below the proposed civic green space which forms the centre of the regeneration project. During discussions with Dundee City Council it was identified that this could become an issue as people may feel put off by crossing busy roads to access the civic space. Figure 8.7 demonstrates the prototypes' current representation of traffic density. The application allows the user to understand the effect of different traffic densities on the sustainability of the development by arbitrarily representing the number of cars present on a particular street.

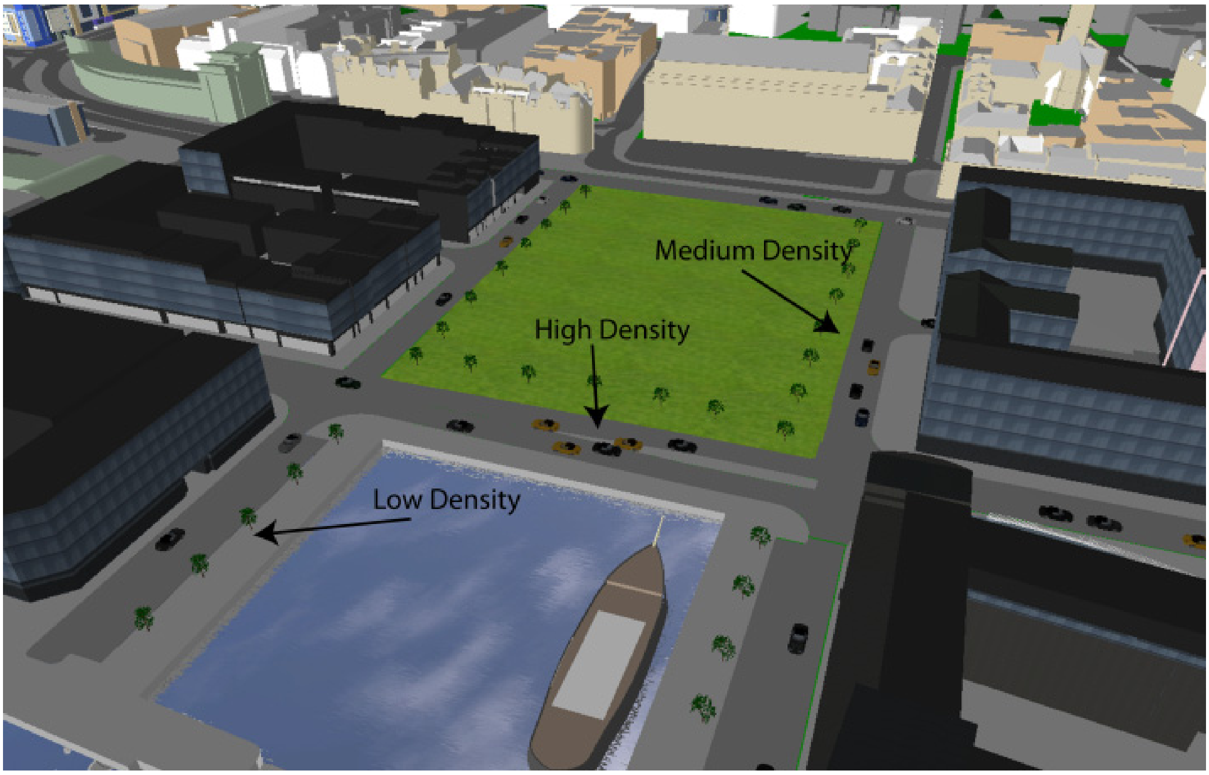


Figure 8.7 Representation of traffic density

One important aspect is that as the user is able to control or change the camera and they are able to view the impact of the traffic at their own level. Therefore it is possible for the stakeholders to see the visual impact of placing tree or other components of the development to help shield the pedestrians from the view of differing levels of traffic.

8.4 Sound

S-City VT also allows for the inclusion of directional sound effects. While this is important in immersing the user in the virtual environment, it also allows another vector of channelling information to the user. Currently S-City VT employs sound to demonstrate the noise pollution caused by different traffic densities. Again this was an issue that Dundee City Council felt was important in making sure that the new waterfront was a inviting place to go. The higher the volume of traffic present on a road, the louder the traffic noise will appear. The traffic noise will also change depending on the distance the user is from the sources of the noise; this helps demonstrate to the user how they may not be able to hear traffic from the green space, or the main pedestrian walkways. Sound effects such as bird song can also be used to demonstrate the effect of urban public spaces, such as parks or greens, on noise pollution.

8.5 Traditional Graphical Techniques

Whilst the visualisation techniques described above provide an abstract way of comparing the sustainability of different scenarios, it is also understood that some stakeholders, especially the expert stakeholders, may not like to view data in this way. Some stakeholders, who are used to viewing the actual data in graphs and tables may feel that the data used in the visualisation are not transparent or the colour scales not obvious. To overcome these perceived difficulties the visualisation tool also contains some graphical techniques, which can show the results of the sustainability models in a more traditional way, in conjunction with the 3D display.

8.5.1 Radar Graphs

Radar graphs, or star plots (Figure 8.8) allow the stakeholder to compare the sustainability of different buildings based on the indicator values. Radar graphs are designed to display multivariate data, where the number of variables is arbitrary (Friendly 1991) and are usually easily interpreted when used for comparisons allowing maximal and minimal values to be easily spotted (Jacoby 1998). In S-City VT the user will be able to select a building from each scenario and compare the radar graphs. There are two radar graphs shown for each building, one which represents the three aspects of sustainability; economy, society and environment, so the user can see which aspect the building is tending to and another which shows the buildings values for the six indicators being modelled. The shape, size, colour and point values will be different for each building allowing a detailed comparison. Radar graphs have been used in sustainability assessment before (as shown in Chapter 2 with the SPEAR assessment) and as such will be recognisable to some of the expert stakeholders and should be used by non experts with little trouble.

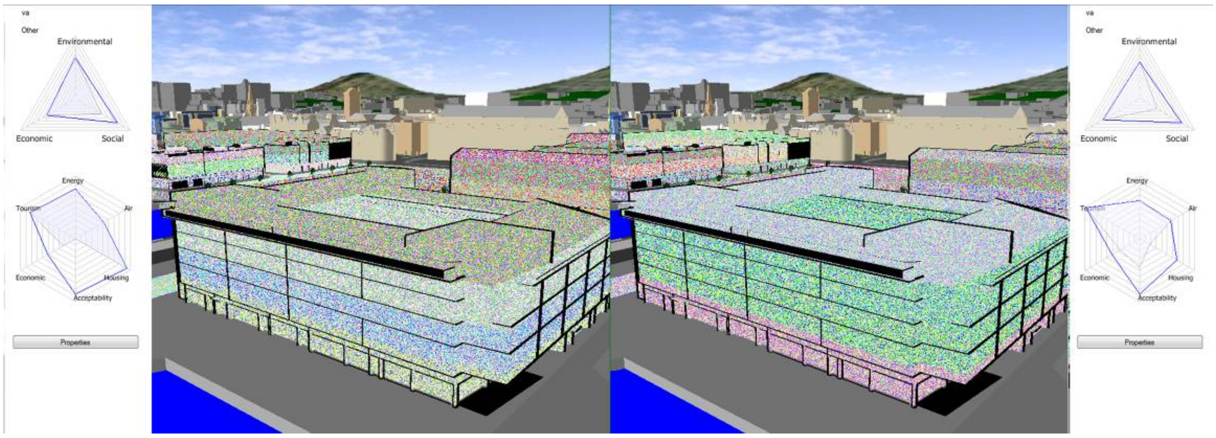


Figure 8.8 Comparison of scenarios using traditional radar graphs and colour weaving.

8.5.2 Parallel Coordinates

Along with radar graphs, S-City VT also includes the option for viewing the output of the sustainability models using parallel coordinate plots. Parallel coordinate plots are frequently used in information visualisation for displaying multivariate data commonly being used in air traffic control collision scenarios (Inselberg 1990). They are especially useful in allowing the user to spot correlations between variables (Wegman 1990). The parallel coordinate plots in S-City VT allow the user to compare all indicator values for all the buildings in a scenario (Figure 8.9). Buildings can be selected and their trace in the graph is highlighted. The colours in the graph correspond to those in the blending technique. The user can select a building in the 3D environment which will be highlighted in the parallel coordinate plot with a thicker black line; the user is also able to see the median building for the whole development highlighted in the plot.

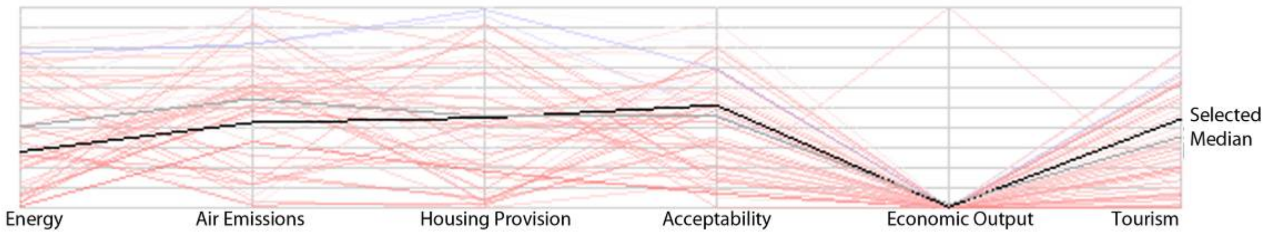


Figure 8.9 Parallel coordinate graph for sample development.

8.5.3 Temporal Graphs

To allow further detailed investigation of the sustainability indices the user can also view simple line graphs. These simple temporal scaled graphs plot the all the indicator values over the life time of the development. These allow the user to identify the interconnectivity of the indicators and to help identify where and why sudden changes occur (Figure 8.10). These temporal plots may be viewed for a single building or the development as a whole.

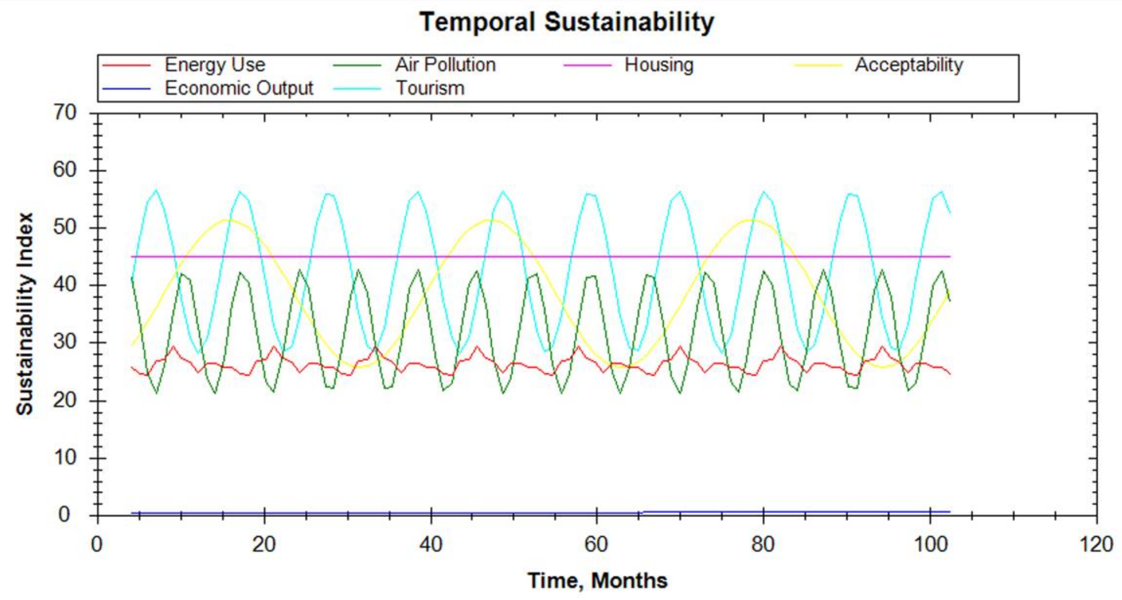


Figure 8.10 Indicator graph showing changes in 6 indicators over time.

8.6 Summary

Chapter 8 describes how the modelling, multi-criteria analysis, scenario design and 3D rendering components are combined with visualisation techniques to present the relative sustainability of any scenario to the user. As shown, S-City VT provides a number of visualisation methods and aims to ensure that a user is not disenfranchised by being forced to use a technique they either dislike or do not understand. The effectiveness of S-City VT at presenting these data and its ability to engage different stakeholders is presented in the next chapter.

Chapter 9 Usability & Effectiveness Testing

The testing strategy of the S-City VT visual DST has been designed to determine if S-City VT does effectively support the decision making process in sustainable urban design through the use of visualisation and modelling. This will be performed by testing if the DST is useable by the stakeholders and if the visualisation techniques used are able to confer the sustainability information to the users. This chapter details the testing hypothesis and the methods by which these hypotheses were tested followed by the results of the testing sessions.

9.1 Testing Hypotheses

1) Stakeholders will be able to identify the virtual environment as a city or urban environment and the elements of the urban environment under all visualisation techniques.
2) Stakeholders will suggest a preference for the 3D visualisation over existing methods of sustainability assessment and displaying urban environments.
3) Stakeholders will be able to discriminate which of the two scenarios presented using the split screen system is the more sustainable.
4) Stakeholders will be able to identify the indicator causing the difference in sustainability.
5) Stakeholders will be able to rank buildings in order of sustainability.
6) Different stakeholders will have a preference for different visualisation techniques.
7) Stakeholders can use the DST to determine the sustainability of a real scenario using a number of the visualisation techniques.

8) The Visual DST will encourage engagement and facilitate discussion around the decisions being made.

9.2 Testing Strategy

The testing strategy is based on the findings of previous research on testing information visualisation techniques (Wehrend & Lewis 1990; Mazza & Berre 2007) which suggest that the questions asked during the testing ascertain both the users' feeling towards the tool, try to identify possible usability problems which might occur whilst using the tool and also to explore the cognitive tasks the user performs with the application. Wehrend & Lewis (1990) suggest a number of domain-independent cognitive tasks that should be addressed during the testing process; a selection of these have been chosen to form the questions that will be put to the testing participants, namely;

- Locate - the user's ability to find something in the visualisation that they recognise;
- Identify - the user's ability to identify something they have not seen before;
- Distinguish - the user's ability to distinguish between different elements of the visualisation;
- Distribution - is the user able to identify the distribution of data?
- Rank - is the user able to rank the items displayed?
- Compare - is the user able to compare the items in the visualisations?
- Correlate – is the user able to correlate between the items in the visualisation?

9.2.1 Section 1: General Questions

The first section will use open ended questions to determine how useful the prototype is in general terms, how good the participants felt the representation of the environment was and how this compared to other methods they were used to. This tests hypotheses 1 & 2.

How recognisable is the environment?

Is the 3D virtual environment representation useful?

What other methods of displaying an urban environment do you know of?

How does this compare to these other methods?

9.2.2 Section 2: Determine effectiveness of display techniques

The second section deals with exploring the cognitive tasks of the visualisation tool. The questions in this section are much more direct allowing the prototypes' effectiveness to be judged. This section will be split into 5 sections representing the different visualisation techniques provided by the prototype. This section tests hypotheses 3-7.

Visualisation off

This section is designed to determine if the stakeholders can identify what the visualisation represents and the cognitive tasks locate, identify and distinguish are also tested:

- *Can you locate an object in the virtual environment that you recognise?*
- *Can you identify what the elements in the environment are in this scenario?*
- *Can you distinguish between the boundaries of each element in the environment?*
- *Can you identify the general building material used for each of the buildings?*

Blend (Single Scenario)

This section is designed to determine if the blend technique still allows the user to identify and distinguish between structures. The users are asked if they can still identify elements in the environment and distinguish between the buildings and elements in the environment to determine if the visualisation technique affects the participants' recognition of the environment. The user's ability to determine the distribution and their ability to rank the buildings using the blend technique are also tested:

- *Can you identify the what the elements in the environment are in this scenario?*
- *Can you distinguish between the buildings/ elements in the environment?*
- *Can you identify the distribution of the data (max sustainability, min sustainability)?*
- *Can you rank the buildings in terms of their relative sustainability?*

Weave (Single Scenario)

As with the blend section the weave section determines if the user is able to recognise, rank and categorise the buildings based on the data being presented using the weave technique

- *Can you identify what the elements in the environment are in this scenario?*
- *Can you distinguish between the buildings/ elements in the environment?*
- *Can identify the distribution of the data (max sustainability, min sustainability)?*
- *Can you rank the buildings in terms of their relative sustainability?*

Comparison using Blend Technique (Split Screen)

This section explores the prototypes' ability to allow the stakeholders to compare different scenarios. The stakeholders are shown two scenarios with differing sustainability and are asked if they can identify the worst option and how they came to this decision:

- *Can you identify the "least sustainable" building in the 2 scenarios presented?*
- *What allows you to distinguish this as the worst building?*

Comparison using Weave Technique (Split Screen)

As with the blend technique, but using the weave technique to display the data:

- *Can you identify the "worst" building?*
- *What allows you to distinguish this as the worst building?*

9.2.3 Section 3: Realistic decision

In the final section the participants are set a more realistic task where they are asked to look at two possible scenarios which could be added to the planned waterfront development. The buildings have the same outward appearance but had different types of building use. The participants are asked to use all of the techniques that they have just seen during the test to determine which whole scenario is the most sustainable and to attempt to ascertain why. The two scenarios are based on a mixed use scenario and a predominately commercial scenario and as such there are a number of indicators which would have differing sustainability indexes. This section tests many of the cognitive tasks already covered in the previous section, but importantly it also determines if the users are able to correlate between the data being shown by the various visualisation techniques and the actual indicators and combine this with their own knowledge to determine the differences in the scenarios.

9.3 Focus Groups

As has been discussed in Chapter 2, one of the major failings of the decision making process is the lack of engagement with all the stakeholders involved. To allow the effective testing of the visualisation tool, it is therefore important that any testing involves this wide variety of stakeholders. As sustainability and planning decisions are rarely decided by one person but by groups of stakeholders at various consultation, engagement and decision making meetings, it is required that a testing strategy be chosen which simulates, as faithfully as possible, the types of consultation and engagement meetings it is envisaged the tool will ultimately be used in. To address the group and stakeholder variety issues, a focus group methodology has been adopted.

Focus group research, although traditionally used in market research, is now being adopted for use in a much wider range of social research (Krueger & Casey 2009). A focus group is a special type of group discussion-based interview that explores a specific set of issues and can be used to better understand people's opinions on these issues (Millward 1995; Krueger & Casey 2009; Kitzinger 1995). Focus groups work under the theory that participants will feel more comfortable discussing their opinions as part of a group where they feel they are not being solely judged. Instead of asking each person questions individually, focus groups encourage participants to talk to one another (Krueger & Casey 2009) and express their ideas using their own vocabulary (Kitzinger 1995). This group methodology will allow a much better insight into the group decision making process than a questionnaire or solo interview and also provides observational data that would be inaccessible without the interactions found in a group (Morgan, 1997). Focus groups are an ideal scenario for exploring people's opinions and concerns.

There are a number of drawbacks, summarised in Davies et al. (2002), which may directly affect the use of focus groups in testing the S-City VT tool. The group may be dominated by an opinionated or vocal group member, or some of the group members may be more reserved in voicing their opinions, which would not be present in a survey or questionnaire. As the interaction is live, the researcher may place greater faith in a participant response than overall findings as they were present when the focus group took place. The responses gained from the discussions in the focus group will usually be in the participants' own vocabulary and may not fit easily with interpretation and summarisation as opposed to a questionnaire which would force the participant to answer a specific question. However, the main drawback may be that the moderator could bias results by knowingly or unknowingly providing cues about what types of responses and answers are desirable. All of these limitations on the use of focus groups are understood and can only be addressed in part by the performance of the moderator during the discussion and in the impartiality of the recording transcriptions. The focus groups will also contain a section of direct questions which are less likely to be influenced by the moderator. It is, however, felt that the benefits of simulating the real world group decision making processes and the insight focus groups provide into the dynamics of a group decision out-weigh these limitations.

9.3.1 Focus group selection & structure

There are a number of different suggestions as to the appropriate size of a focus group for non-commercial topics ranging anywhere between five and ten participants (Millward 1995; Gilbert 2001; Krueger & Casey 2009; Morgan 1997). All sources though agree that if the group is too large it will be difficult to control and the size will limit the depth of the discussions and also the ability of participants to express their own opinions. A small group will lead to further discussion with more individual input, but will also lack the range of opinions provided by a larger group (Gilbert 2001; Krueger & Casey 2009; Millward 1995). The focus groups used for the testing of S-City VT attempted to strike a balance between the two extremes being composed of between five and eight members to allow the greatest range of opinions, without reducing the depth and substance of the discussions (Gilbert, 2001).

As suggested by (Krueger & Casey 2009) focus groups should be characterised by their homogeneity, but with sufficient variation. If the group is composed of people with too close a viewpoint, the discussion may be too one sided. However, if they are too different one viewpoint may be suppressed by another. To allow for this and to reflect the varying stakeholders, it was decided to recruit the focus groups from specific stakeholder groups, with each focus group being composed of members of, as far as possible a single stakeholder group (e.g Planning & Transport, Economic Development, Engineers, Community Groups) or closely related groups.

9.3.2 Focus group composition for final testing

The groups selected for the final testing study were as follows (due to the anonymity promised to the participants these groups are not listed in the same order as they appear in the results section):

Group A - Mainly civil engineers form the City Engineering Department and the city's Public Art Officer.

Group B - Local authority planning and transport, roads and economic development experts from a largely rural county with urban centres.

Group C - Local authority planning and transportation, economic and regional development staff.

Group D - Local authority planning and transportation, economic and regional development staff.

Group E - City Community Group.

9.4 Test Procedure

Each focus group session was split into three sections using the example questions detailed in section 9.2. Even though some of the questions were direct, the groups were allowed and actually encouraged to discuss any matters arising from their use of the tool. This approach allowed the effectiveness of the tool to be recorded but also the feelings and dynamic of the groups whilst using the tool to be studied.

During the comparison tests the stakeholder groups were presented with eleven sets of comparisons for each visualisation technique. Each comparison set comprised two scenarios, running simultaneously using a split screen display, as shown in Figure 9.1**.** The two chosen scenarios have different potential levels of sustainability. The order in which the sets appear were generated randomly from a known set, which would produce differences between the sustainability indexes of between 0% and 100%.

Originally there was a difference of 20% between each set i.e 100, 80, 60, 40, 20, 0, giving a minimum difference of 20%. However pilot tests performed by three groups showed that all participants were able to use the blending technique to determine which scenario was the most relatively sustainable and that all participants were able to determine, through the use of the weaving technique, which indicators were the causing the greatest impact. The results of the pilot tests determined that the differences in sustainability in the final test would have to be reduced to determine a minimum level at which the stakeholders can no longer ascertain the difference between the indicators. For the final test the known set of sustainability differences was reduced to 100, 80, 60, 40, 20, 10, 8, 6, 4, 2, 0% giving a minimal difference of 2%.

As well as the difference between the scenarios being randomly selected, the side of the screen that the most sustainable scenario appeared on was also random and for the weaving technique the indicator causing the difference was also randomly selected. The order and the scenario with the highest sustainability was also unknown to the moderator and could only be viewed on completion of the focus group process, this made it less likely that the moderator could inadvertently lead the group to a decision.

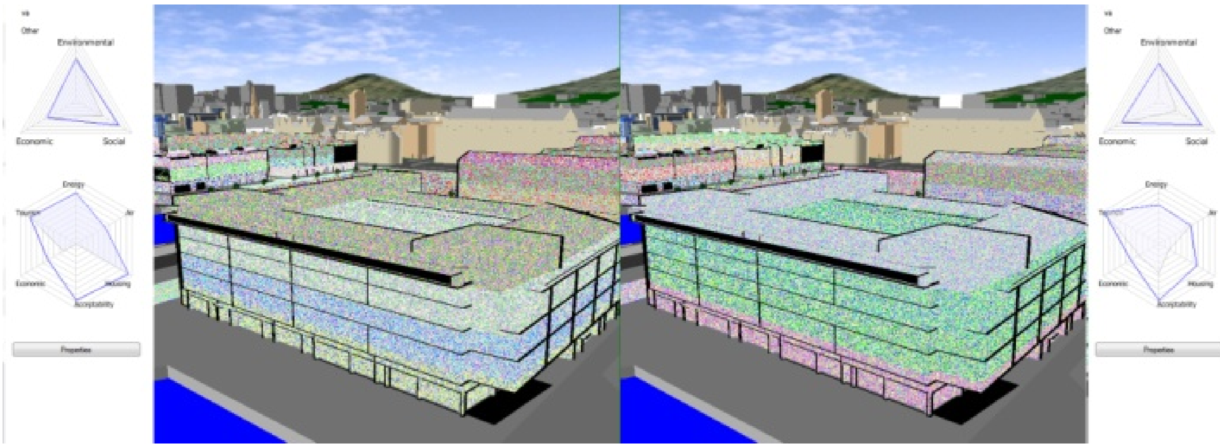


Figure 9.1 Example of split screen view

Each focus group session was overseen by a moderator who asked the directed questions and would also prompt the participants to encourage discussion or to ascertain the groups' feelings. The results of the directed questions were recorded by an observer who would also record observations such as the participants engagement levels and body language. An audio recording was also be made of each focus group, to allow transcriptions to be made which could be used to identify how each group found the use of the tool. The transcriptions coupled with observers comments about the groups will be used to test how effective the tool is at facilitating and engaging the participants (hypothesis 8).

9.4.1 Transcription Analysis

Abridged transcriptions were performed by the session moderator for each of the focus group sessions. Full transcriptions were not used due to the large introductions and debriefs. These sections, along with irrelevant comments are the only portions of the focus group transitions that have been omitted. Having the moderator of the session, who is directly involved in and understands the research, transcribe the focus groups in this way allows the moderator to identify redundant information, such as the introductions, and concentrate on the main body of the focus group session (Krueger & Casey 2009).

9.4.2 Identification of Themes

The transcriptions of each focus took group took place in 3 main stages, following a classical analysis approach. The analysis was performed using the NVIVO software (version 8). Stage one involved the systematic analysis of each group in turn , and the identification of separate issues that were raised in each group; each of these issues is coded into an NVIVO node. During this stage only comments which were identical or extremely similar were added to the same node.

Once the process of identifying all the spoken references in each group is completed which may be present in one or more of the focus groups. Stage 2 is an iterative process where at first many themes will be identified and then rearranged creating a hierarchy of major and sub themes by merging the nodes identified in stage 1. (the original identified themes are shown in Appendix 2) This hierarchy was then revised to produce the seven major themes described below:

Screen Issues

Many of the group mentioned issues surrounding how the screen used to display the prototype possibly impacted their ability to determine the differences between the scenarios. These comments are referenced here along with aspects such as the room lighting or reflections caused by the position of the screen.

Visual Impairment

Any references made by the groups relating to any visual problem which may affect a user's ability to use the prototype, which include colour blindness, short sightedness and any other visual accessibility issues.

Visual Appearance

Visual appearance relates to how the focus groups thought the prototype looked, which includes any aspects they thought were visually appealing or distracting, helped them recognise the environment and issues with how realistic they thought the visualisation was.

Interactivity

Interactivity relates primarily to the movement of the camera to control the view of the environment. Participants' requests to move or otherwise change the view or comments on the interactivity of the tool are recorded here.

Blend Scales

The participants comments on the use of the blend technique, any issues or confusion the colour maps caused.

Weaving Issues

Any issues raised during the participants' use of the weaving technique, including problems, suggesting and feelings which arose.

Decision Discussions

References to the discussions over the decisions being made were recorded in an attempt to ascertain how the group interacted with each other. Not simply counting one member suggesting an answer and the other members of the group agreeing , the decision discussions theme was a recording of when the groups actively discussed the decision.

The final stage of the process was to create a description of how each group felt about the tool based on the identified themes. This was completed by determining the proportions of each referenced theme in each focus group. As these proportions alone may not give an accurate reflection of how important each topic was to the group when combined with the observations recorded during the focus group sessions and examples of the expressiveness of the groups' statements, an idea of the focus groups' feelings in each of the themes can be determined.

9.5 Summary of Results

The summary of the focus group results are outlined below, however the full analysis of each group is available in Appendix 1 along with the abridged focus group transcripts in Appendix 5 (on attached CD).

Please note the summary below will reference material in the appendices using the following format A1.2 refers to Appendix 1 section 2.

9.5.1 Summary of Section 1 General Questions

All the groups suggested that the virtual environment was recognisable as an urban environment and specifically recognisable as Dundee. All the groups seemed to agree that the 3D virtual representation was useful, especially in terms of providing a sense of scale and context into which the user can view the proposed development from unrestricted camera angles and understand how the proposed development can fit with what has already been built.

The groups suggested various methods that they already used for displaying urban environments both in planning and consultation. The methods were maps, physical models, photomontages, site visits, pictometery, Google SketchUp and GIS. Of these methods the most commonly mentioned was maps and physical model; surprisingly GIS was only mentioned by one of the groups. It is possible the word “displaying“ in the question could have affected the group's answers, it is also possible that when mentioning maps the groups were actually referring to GIS. What was clear was that the groups felt that none of these methods, with the exception of SketchUp, provided the range of views or context which could be easily understandable. It was expressly stated by many of the groups that people, not necessarily non-experts, have difficulty imagining what is proposed from 2D imaging such as GIS. Physical models were sometimes developed by the group to aid in the consultation and design of a development to give a perspective of what the final development may look like, but it was also stated that this would not provide the context that a virtual environment does and also it is hardly ever done due to its prohibitive monetary and person hour costs. One method mentioned which does utilise virtual environments is Google SketchUp, however it was conceded by this group that even this did not provide the ease of use that would make it accessible to wide range of stakeholders. One group highlighted that certain methods such as photomontages can be unrealistic due to certain fixed view angles or focal lengths on the finished images. It was also implied that it is common practice, in some areas, for this manipulation to be performed deliberately to misinform the public or the planning office as to what a building or structure will actually look like when built.

Statements such as “simply amazing” and “absolutely unique” made by some of the groups show that even as experts they are rarely exposed to this kind of decision support tool, which reinforces the findings of the literature review which highlights that decision support tools, especially with a visual component, are rarely used.

The group responses to the first section show that all the groups felt that the 3D virtual environment did have advantages over the methods they currently used and were enthusiastic about its possibilities; this is clear from the transcripts and also the notes taken throughout the focus groups. The one group that was more reserved were much more involved in the actual development used as the case study and in had invested in the software they were already using.

9.5.2 Summary of Section 2 results of tests on the effectiveness of display techniques

All of the groups were able to identify at least one of the main landmarks in Dundee such as the Discovery Centre, the Discovery Ship itself, the Law, the war memorial and the Tay Road Bridge. This shows the importance of landmarks in helping the stakeholder identify the context of the scenario or development. One of the groups went as far as identifying other, less detailed, objects based on sightlines between the landmarks that they did recognise. This shows that the tool was effective at allowing people not only to recognise the city or urban landscape from a distance but also to recognise the more detailed landmarks that many residents would identify their city with.

When asked about the building materials being shown on the buildings in the development, all of the focus groups that were asked suggested that it would be possible to get a fair idea, or make a guess at what building materials were present but it would strongly depend on the camera distance from the object. It is clear from the groups answers to this question that for stakeholders to correctly identify building materials, the textures on the buildings should be more detailed. This shows that if the purpose of a comparison is to compare representative images of different building materials then the tool is effective, however if the tool is required to accurately reflect what a building material actually looks like then more detail would have to be added.

When ranking a number of buildings in a scenario, both visualisation techniques caused problems for the groups. Using the blend technique, all the groups were able to determine which building was the most and which was the least sustainable, however they were unable to rank buildings whose sustainability indices were very close together. With the weaving technique some of the groups were able to identify the most and least sustainable building but expressed that they found this much harder to do than with the blend. None of the groups found they were able to rank the buildings and a few were put off from trying from the initial appearance of the weave technique.

Visualisation techniques

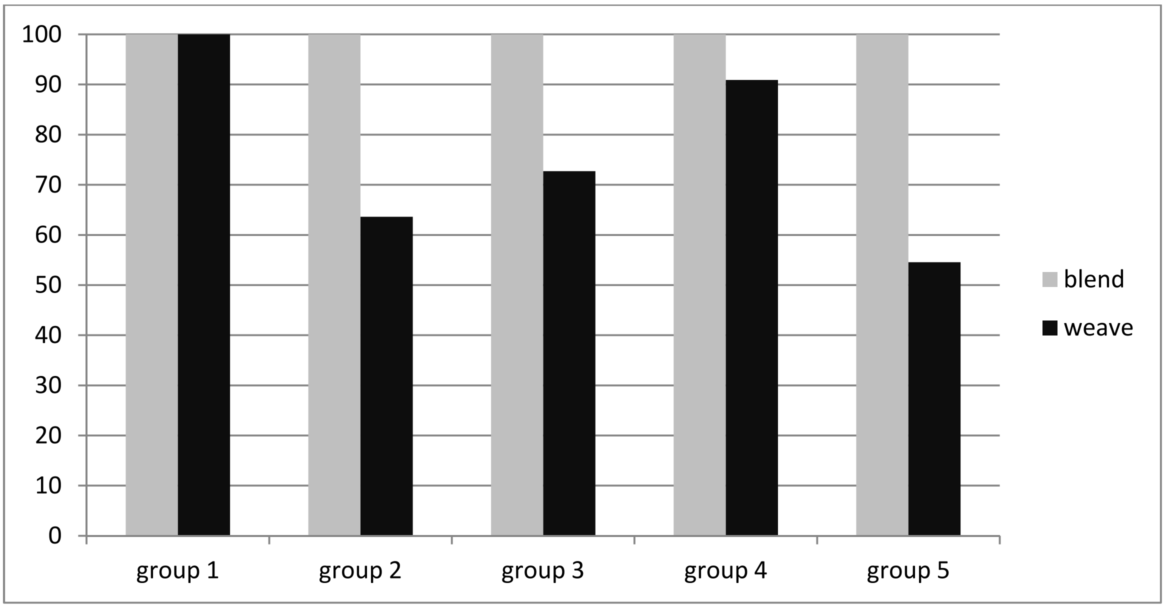


Figure 9.2 Proportion of correctly selected scenarios using the blend and weave comparison techniques for all the focus groups

The comparison test results (Figure 9.2) show that all the groups were able to successfully identify the most sustainable scenario using the blend technique. However, they also show that some of the groups were not so successful at determining the difference between and identifying the indicators whilst comparing the scenarios using the weave technique. This reflects the difficulty that the participants had with the weave technique.

9.5.3 Summary of Section 3 choice comparison based on a realistic scenario decision

Table 9.1 Summary of choice comparison results

Group	Correctly identified changing indicator	Wrongly identified changing indicator	Indicators not mentioned	Correct scenario identified
1	4	0	2	yes
2	4	0	2	yes
3	5	0	1	yes
4	1	1	4	no
5	3	0	3	no

From the results of the choice comparison (Table 9.1) it can be seen that most of the groups were able to identify some of the indicators that were different between the scenarios and that three of the groups were able to identify the correct scenario using the blend technique. Two of the groups (4 &5) were unable to correctly identify the scenario; it is believed from the recorded observations that this may have occurred due to confusion between the colour scales, especially the red blue scale, a phenomenon which is discussed in the next section. All of the groups when using the weave technique to identify the changing indicators, did not mention at least one indicator in their discussions. One indicator that all the groups did not mention was noise pollution which did not change between the two scenarios, which may indicate that the groups were concentrating on the indicators they thought were changing. However, groups 4 & 5 did not identify almost half the indicators that were changing and group 4 incorrectly identified noise pollution as changing between the scenarios.

9.5.4 Summary of focus group observations and transcription analysis

Identified Themes

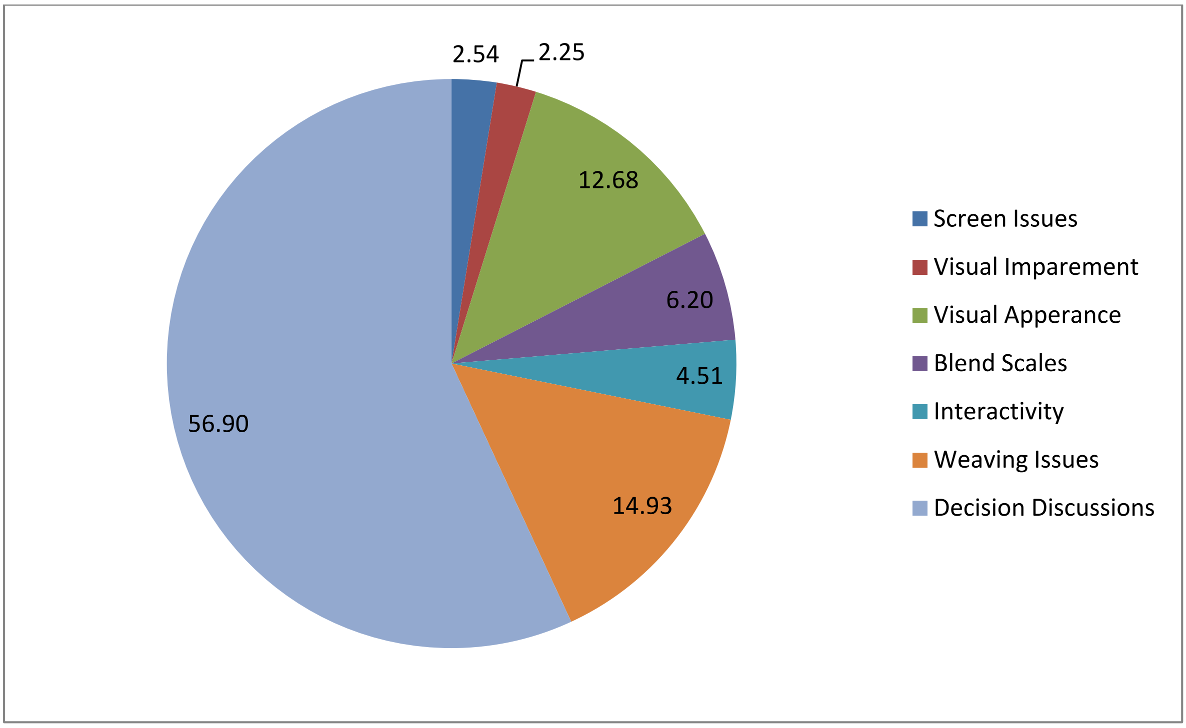


Figure 9.3 Proportion of references assigned to identified themes combined across all groups

Figure 9.3 shows an overview of the themes identified through analysis of the transcriptions and observatory notes taken during the focus groups. The proportions were derived from the number of references to an identified theme. As counts alone do not necessarily reflect the expressiveness or importance of a particular theme, these have been combined with observations recorded during the groups to provide the discussions about the themes below.

Screen Issues

All but one of the focus groups mentioned that they felt there was an issue with the screen which may have affected their ability to discriminate between the scenarios in the comparison tests. The same screen was used throughout all the focus groups so the screen its self remained constant, however the lighting and the angle the viewers were to the screen could not be controlled in every environment that the prototype was tested in. The main issue seemed to be that when the sustainability indices of the scenarios were close together, the angle the participant was viewing the screen from seemed to affect the colour that the participants were seeing. When it was clear that the participants were seeing a different colour depending on their angle they were encouraged to move around, which helped the groups make their final decisions about which scenario to choose. This issue did not seem to affect what scenario was picked as the most sustainable but rather what colour or indicators was causing the greatest effect. Two of the groups, group 1 (A1.1) & group 3 (A1.2) also suggested a problem with the screen being too shiny and that this may affect their ability to differentiate between the scenarios due to reflections of colours from the testing environment.

Visual Impairment

Visual Impairment, in particular colour blindness was mentioned by all the groups with the exception of group 3. Mainly the issues arose around the weave technique and whether someone with colour blindness would be able to determine a particular indicator. One of the participants of group 1 (A1.1) stated that they were colour blind; however this was only mentioned quite late in the study. During a close weave comparison the group member was unable to determine the colour that had changed although they were able to tell which scenario was the more sustainable. This visual impairment did not seem to effect the colour blend tests, which was supported by a member of group 5 (A1.5) who suggested that colour blind people may be very good at picking a shade or hue of a colour but not identifying what the colour was. During focus group 4 (A1.4) one of the participants could not understand why the moderator and the other group members were describing the red-blue scale as red-blue when the participant was detecting shades of red as green. This did not seem to have an effect on the participant being able to choose the more sustainable scenario using the blend scale, however not being able to describe the colour in the same way as the other participants seemed to irritate the participant, although they were more than happy to continue. During the course of the focus group it was noticed that this could also have been an effect of the screen angle.

Visual Appearance

The realism of the virtual environment was discussed by a number of the groups and a number of issues were raised. Group 3 (A1.3) asked about the validity of the background data, in particular the accuracy of the LIDAR data and whether it had to be manipulated before being added to the visualisation. They were also asked about the possibility of applying render to the buildings surrounding the water front so that it looked even more realistic and how long this process would take. Although it was also mentioned that having the periphery buildings, not involved in the decision, at a lower detail still provided context for the decision but drew the viewers' attention to actual development in question. Realism was also mentioned by Group 2 (A1.2) suggesting that in parts it was too realistic, "better than real life", due the lack of atmospheric effects. It was suggested by the group that atmospheric effects such as haze or sea haar (coastal fog), which is often present in Dundee, could affect the perceived distances between objects in the city making them seem closer. As the visualisation does not contain these effects, some of the landmarks may not appear to be the correct distance from each other from certain camera angles. Focal length was also mentioned as something that other techniques, such as photomontages, had used to "skew" or "cook " images and it was asked whether the focal length for the virtual environment was accurate or could be changed. Both Group 3 and Group 2, however, also suggested that the visualisation is "not necessarily meant to be accurate" and that "details maybe aren't important" suggesting that they believed that a representative visualisation was enough. Many of the groups commented on the virtual environment's ability to add context and a sense of scale to the proposed development that is not possible using many of their existing methods, however Group 2 noted that this sense of scale could be enhanced if visual cues were in place to allow a comparison against something of a known fixed height, such as a person.

The water in the visualisation is represented realistically using a pixel shader designed to imitate the movement and reflections of the river beside the proposed development. It was noticed during early development that using this realistic rendering during the weave and blend comparison tests could distract the user from the scenarios. To overcome this when the comparison tests are started, the water is simply represented by a solid blue colour. It was suggested by a number of the focus groups (A1.2,A1.3,A1.5) that this colour is too strong and could have affected their ability to discriminate between the scenarios.

Interactivity

The ability to move the camera seemed important to many of the groups, especially the zoom function which many of the groups used to help them identify either aspects of the virtual environment such as the building materials used or to help them compare scenarios during the blend and weave tests. Group 1 in particular extensively asked for the virtual environment to be zoomed in and out during the test when they were having trouble identifying a specific detail. It was also suggested by the group that "the ability to zoom in is important because if people don't have very good vision it could be really difficult to pick out that detail" and that "if you were having difficulty distinguishing, you could actually move about" to enable a better understanding of what was being shown (A1.1).

Group 4 (A1.4) suggested that the interactivity provided by the application would allow for more people, specifically the younger generation, to engage with the planning process. They believed that the younger generation would be enthusiastic about taking control over the environment and looking around. Whereas the group themselves maybe would not have the confidence to move about the environment, one participant stated that they did "not do technology", but would have the confidence to ask a facilitator to move the view about for them.

Blend Scales

Most of the groups expressed a preference for the red- blue scale with the exception of group 4 (A1.4), whose members preferred the greyscale. The other possible scales were not used or preferred by any group although it was suggested that having the ability to change the colour scale was important as what suits one group may not suit the next.

A few groups became confused in mapping the colours shown to high and low sustainability when changing between the weaving and blending techniques. Suggestions such as using the "weave scale, low sustainability is strongest and it fades out whereas you seem to get darker here at higher sustainability" and "so it stays paler or something" highlight this confusion between the scales. Group 4 (A1.4) in particular had the most issues with mapping the colours to values where, on a number of occasions the participants asked why the scale had changed from dark meaning low sustainability and light meaning high sustainability, when in actual fact the scale had not changed whilst using the gray-scale for the blend test and during the weave tests the lighter a colour always represents a higher sustainability. One particular participant asked this question for every scenario comparison and seemed unable to identity each time which colour linked to which level of sustainability. The reason for this confusion seems to stem from the red-blue scale being mainly used or visible on handouts given to the group. Using the red-blue scale a dark blue will represent high sustainability and a dark red low sustainability however when using any of the other scales and the separate scales used in the weave techniques a lighter colour always represent a higher sustainability. It could also be possible that the key to the current scale on the screen was not clear or visible enough and that some of the groups used memory rather than looking at the scale to identify the sustainability levels this seems to be confirmed by a member of group 3 (A1.3) who suggested that it took a few moments to get used to the new scale.

Weaving Issues

All of the groups found the weaving technique much more difficult to use than the blend technique. The groups made comments about how hard, complex and unsuitable the weaving techniques was in general, suggesting that it would "take a lot more explanation" (A1.2) , was "very difficult" and "too busy" (A1.4) and the user "could put it into something more suited to your preconceptions" (A1.2). Many of the groups made it clear that they were struggling with the weave at different points during the test comments such as "I'm struggling with that", "I can't pick anything out" and "oh god". Perhaps the clearest indication of the participants fatigue with the weave test came in group 3 where on participant commented "I have to say that I've switched off, I can't concentrate enough to make it out".

Many reasons for this difficulty were suggested by the groups, such as the key was positioned over part of scenario 1 and this could distract from the indicator colours on the weave, that the arrangement of some of the colours, especially the turquoise and the green being beside each other or that some of the colours used for the weave technique we more dominant, such as red and blue and that these may washout the less dominant colours cyan/turquoise and yellow made it harder to recognise a single indicator change.

Some of the groups suggested that in a real world situation they would want to see more information especially when the scenarios being compared were extremely close. One member of group 2 suggested that when the scenarios were very close the user may find a difference when there is not one, stating “that you start really focusing and looking for a difference and that will just be trying too hard“. Group 5 seemed to be the most reluctant in selecting a scenario base solely on what was being shown expressing that even for the large differences they would want to know “exactly what’s running” and what each individual building was.

Three of the groups (A1.1,A1.2,A1.3) developed methods which attempted to overcome their difficulty in using the weave technique to determine the differences between the scenarios. Group 1 and group 3 took the approach of identifying patterns like T or an L, suggesting that you “look at the pattern, take a corner and look at it”, and then were able to determine if the colour was different in this shape. Group 2 took a similar approach suggesting that it was easier if the colour comparison was based on two blocks.

Groups 2, 3 and 5 suggested some alternatives to using the weave technique such as using simple bars or chunks drawn on the buildings to demonstrate the sustainability, group 2 suggested adding a key which blocks the scales into percentiles, or actual percentage figure on the scale showing where each scenario is to allow the user to better identify the most sustainable scenario. Although one member of group 5 recognised the reasoning behind the weave was to have a display method which functioned irrespective of the building size.

Two of the groups, 2 & 3, noticed what is thought to be an optical illusion where the buildings in one of the scenarios may look bigger than the same buildings in the other scenario. This illusion, which only seemed to affect the weave technique, would only occur when the camera was at particular angle.

Decision Discussions

From Figure 9.3 it is clear that across the groups the discussions about the sustainability of each scenario during the comparison tests formed the large majority of the counted references. Counting the amount of discussions about the scenarios for each group, and comparing this to the observations noted about how the participants interacted with each other during the focus group, would seem to show that this gives a reasonable representation of how engaged the group was in the process.

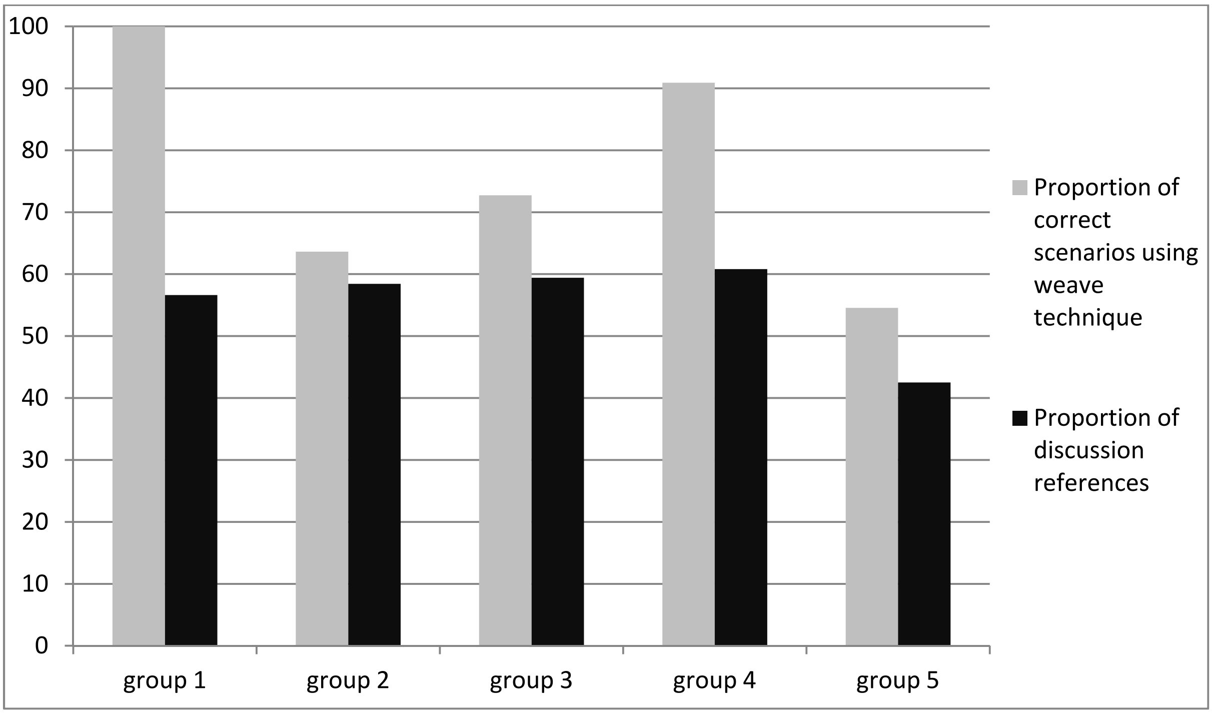


Figure 9.4 Graph showing performance in scenario comparison using the weave technique to proportion of sustainability discussion

As shown in Figure 9.4, the group with the lowest proportion of references assigned to sustainability discussions, group 5, is also the group which performed the worst at the weave technique. This is also highlighted in the notes taken during this particular focus group where it is clear that the group became fatigued during the test and little discussion was entered into among the group once an initial selection had been made. It was also evident that there was a hierarchical phenomenon in effect during this group where one senior member made a selection and the others agreed.

In groups that performed better, there was evidence of discussion which led to a shift from an initial incorrect decision to a final correct decision. From the observations during the groups, this seems to happen quite often during the weave technique comparisons where one selection will be made and then other participants will suggest alternatives until a consensus or compromise is arrived at which tended to be correct. It was uncommon that the group would initially select a correct scenario and then talk themselves out of this decision.

Group Dynamic

It was noted from the observations made during the focus groups that each group had a different level of engagement with the process. To discover how much of an effect engagement had on the group performance in the tests, the amount of references assigned to each participant and to the moderators were counted; the proportions of these references are supported by the observations during the groups.

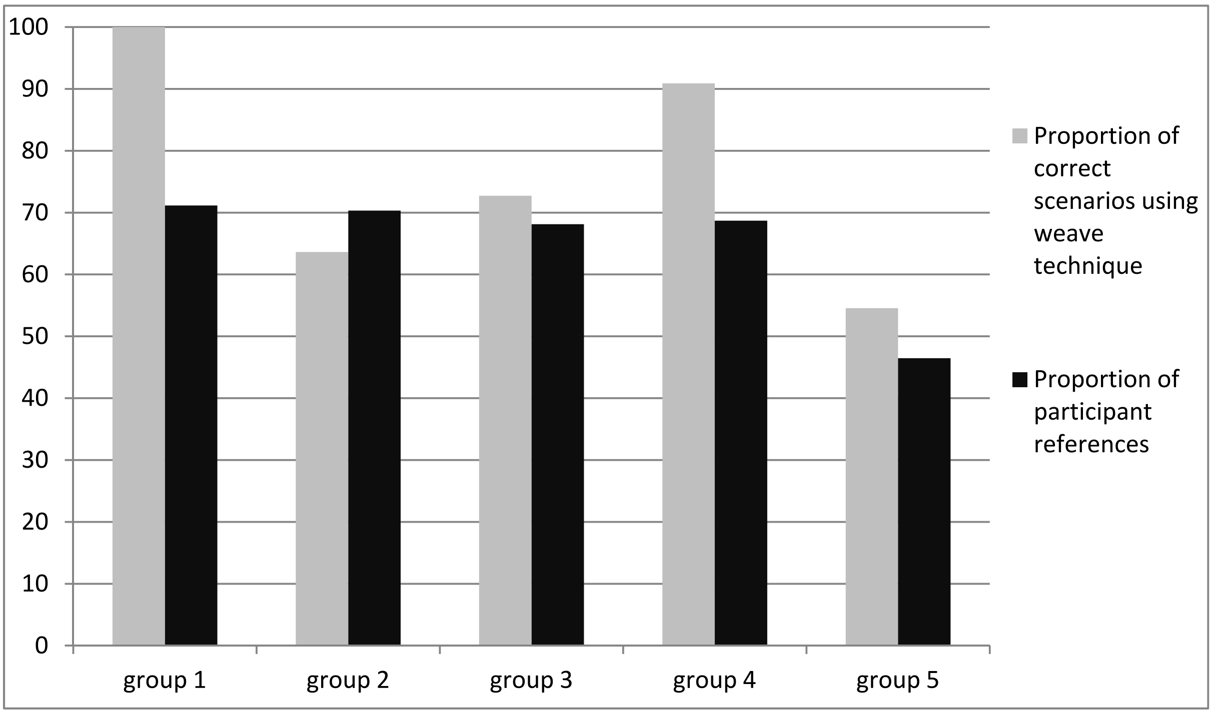


Figure 9.5 Graph showing proportion of discussion references against performance in comparison tests using the weave technique

From Figure 9.5 it can be seen that the group with the lowest proportion of participant references, and from the observations during the group needed the most prompting and encouragement from the moderator, has performed the worst in the comparisons using the weave techniques. As stated before, this particular group seemed to become fatigued with the process towards the end of the weave comparison test, which is supported by their performance in the test and also the observations made by the moderation team. This seems to show that the weave technique works best when the group is interested and engaged in the process.

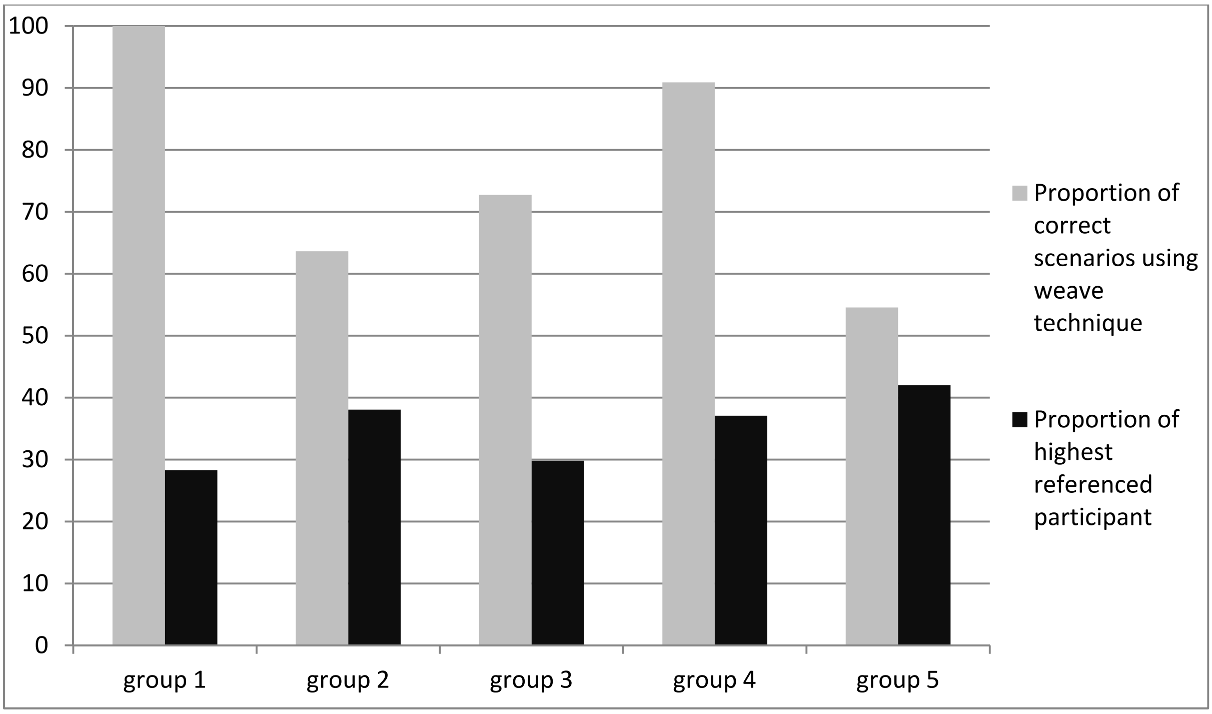


Figure 9.6 Graph showing proportion of most dominant speaker against performance in comparison test using the weave technique

As with the amount of direction which was needed by the moderation team, it was also noted that there was a difference between the groups in terms of whether there was any speaker who appeared to dominate the group. To support the observations, the number of references to each speakers in each of the groups was compared to determine if there was a particular speaker who may have dominated the discussions. The full descriptions of the group dynamic are covered in Appendix 1, however it was shown, both from the reference counts and the notes taken, that there was possibly one speaker dominating the discussions in groups 2 and 5. When these were compared to performance in the comparisons using the weave test it seems to show that these groups have performed the worst.

9.6 Conclusions of Testing Results

The results for the usability and effectiveness focus group tests show that the decision support tool fulfils many but not all of the test hypotheses.

All the focus groups were able to identify the city as an urban environment and were still able to do this whilst either visualisation technique was being used as such test hypothesis 1 can be accepted.

Many of the focus groups did express either a preference for the 3D visualisation or suggested benefits that it had over the techniques they currently used or were aware of for displaying urban and rural environments. It is not clear, however, if the focus groups preferred the DST over other methods of sustainability assessment as no other methods of sustainability assessment were identified or mentioned by any of the groups. Hypothesis 2 cannot be rejected or accepted at this stage and more comparison against existing sustainability assessment tools would need to be performed.

From the results of the blend test, all the focus groups were able to determine the most sustainable scenario using the split screen technique down to a difference of 2%. All groups were also able to determine when the scenarios had the same sustainability index level. However, not all groups were always able to do this using the weave technique. Hypothesis 3 can therefore be accepted as long as the difference between the scenarios is greater than 2% and that either the blend techniques or both visualisation techniques are used to compare the scenarios.

The focus groups were not always able to determine the indicator causing the difference between the scenario, with only one group being able to do this for all the scenarios tested. The highest difference between the scenarios that a group failed to spot was 20%; in this case hypothesis 4 can be accepted for differences over 20%.

None of the focus groups suggested they were able to rank the buildings using either techniques; hypothesis 5 can therefore be rejected.

None of the focus groups expressed a preference for the weave technique over the blend technique with all of the groups expressing that they found the weave technique harder to use. The group with the best performance using the weave technique was an expert group, however so was the group that performed the worst. Whilst using the blend scale the non-expert group expressed a preference for a particular colour scale, however from the observations taken at the meeting this may have been more to do with age than the group expertise in sustainability assessment. These results indicate that hypothesis 6 should be rejected.

During the test of the realistic scenarios not all the groups were able to identify the most sustainable scenario. The reasons for this can be identified by analysing the discussions during the meetings and it is clear that there is some confusion between the colour scales used for the blend and the colour scales used for the weave. Some groups identified a deep blue whilst using the blend scale (which indicates a high sustainability) with the deep blue used in a weave scale (which indicates a low sustainability), this confusion was not endemic to a particular type of stakeholder. As such, hypothesis 7 cannot be rejected or accepted at the present time as some groups were able to identify the most sustainable scenario.

The observations and the transcription reference count show that by far the highest proportion of the focus group sessions were spent discussing the decision to be made. When the groups' performance using the colour techniques is compared with the observations and transcription counts, it would seem that the groups that performed the worst also discussed the decisions they were making the least. There is also evidence that those groups that did discuss their decisions more frequently corrected decisions that they may have initially misinterpreted, while those groups that did not discuss the decisions stuck with an incorrect choice. This seems to show that the tool did provoke discussion among the focus groups and in fact those groups with the highest level of discussion made more correct decisions, which infers that hypothesis 8 should not be rejected.

Chapter 10 Conclusions & Future Work

10.1 Introduction

The conclusions of the research have been developed by assessing to what degree the aims of the project had been achieved and therefore whether the overall hypothesis of this research can be rejected or accepted.

The main project aims were:

- To evaluate and identify gaps in existing DSTs and sustainability assessment methods.
- To identify where visualisation techniques from DSTs used in other disciplines can be applied effectively in decision making for sustainable urban design.
- To create a prototype interactive simulation and visualisation decision support system, the Sustainable City Visualisation Tool (S-City VT) that can assess and communicate sustainability information to both expert and non-expert stakeholders.
- To determine the usability and effectiveness of the tool and the underlying visualisation with different stakeholder groups, including local authorities and the general public.

The overall hypothesis was:

Can 3D visualisation and modelling be combined into a single decision support tool to effectively support the decision making process and engage both expert and non-expert stakeholders in the development of sustainable urban environments?

The review of existing decision support tools and sustainability assessment methods was presented in Chapter 2 where existing decision support tools for sustainability were evaluated and decision support tools used in other domains were investigated. The conclusion of these sections are presented below.

10.1.1 Review of existing tools for sustainability

From the review of existing tools used in sustainability assessment it was clear that many tools exist for this purpose. All of the tools reviewed fitted quite neatly into one of the categories; model based, process based, ratings based or visual based. This ease of categorisation highlights the fact that no single tool exists that is fully integrated, covering all the required functionality of a DST which would effectively support decision making but also engage both expert and non-expert decision makers alike. It was also clear that few, if any, of the tools could be used fully by non-expert stakeholders and none of the DSTs presented, with the exception of the CSA checklist, were specifically designed for use by non-experts, even though there has been extensive research to show that effective decision making in sustainability decisions can be achieved only through the inclusion of all stakeholders.

The review did, however, reveal a number of different processes that could be incorporated into a new DST designed specifically to overcome some of the problems associated with existing decision support tools for sustainability. Some of the model based DSTs used a sub-model approach which was adopted by the S-City VT tool, as were radar diagrams, similar to those used in the ranking based DSTs. Multi-Criteria Assessment was also adopted as a way of weighting and aggregation of the sustainability indices used to drive S-City VTs visualisation component.

It can be concluded that the first project aim has been fully achieved and that whilst DSTs for sustainability do exist and many utilise beneficial techniques, there is no tool which allows all stakeholders to engage in sustainability decisions. This supports the research hypothesis that there is a need for a new DST which can increase the engagement levels in urban sustainability decisions.

10.1.2 Identification of visualisation techniques used in other disciplines

Section 2.3 highlights how visualisation techniques have been used for decision making in a number of domains other than sustainability assessment. The tools identified were shown to either concentrate on the display of spatial data involved in the problem being addressed (GIS) or to concentrate on presenting the physical appearance of the environment in which the decision is being made. It was, however, clear that those tools which utilised games engines to present the physical environment could provide not only a high quality, engaging visual component, but also had the potential to provide the kind of interactivity that has been lacking in existing DSTs for sustainability.

Techniques such as using colour and colour weaving were identified and it is believed that these techniques could provide a way of bridging the gap between a purely visual DST utilising a games engine, such as the wind farm examples, and the traditional, non-visual model based DSTs.

The identification of these techniques which were used to determine the development path of the S City-VT tool achieves the second project aim and the ability of computer game engine based DSTs to provide a more interactive and engaging user experience supports the research hypothesis.

10.2 Development of S-City VT visualisation & simulation

Chapters 4 to 8 describe how the separate components of the S-City VT tool have been developed to address the problems identified with existing DSTs. These were;

- indicator modelling to quantify the sustainability of the scenarios;
- multi-criteria analysis to allow stakeholder experience and feeling to influence the decision, scenario development to create and modify an unlimited amount of scenarios which can be assessed;
- 3D visualisation to communicate the output of the sustainability models and to allow the comparison of the scenarios being assessed.

By combining these components, the development of S-City VT shows that it is possible to develop a novel DST for sustainability, which provides the ability to model sustainability and, through visualisation, compare or rate an unlimited number of possible development scenarios.

S-City VT was developed bespoke and in a modular fashion to be as flexible as possible. The use of a custom rendering engine allowed techniques and effects to be added as they were identified, which ensured and will continue to ensure that the system can be updated as required. This modular design is extremely important for the sustainability indicator sub-models, as the models can be modified, updated or replaced as desired. The development of custom components which were created in parallel ensures an extremely close coupling between all the components, which would not be possible had existing “off the shelf” solutions been used.

The development of the visualisation techniques, using colour, metaphors, radar graphs, parallel coordinates and traditional temporal graphs provides S-City VT with the ability to communicate the sustainability of a scenario. This range of techniques ensures that a user is not forced to use a technique they do not like or understand in order to assess the sustainability of a scenario. Allowing the user to choose which technique to use acknowledges that different stakeholders will prefer different methods of accessing the data and comparing the scenarios. This is also reflected in allowing the user to choose different colour scales whilst using the blend technique, which may compensate for some visual impairments.

The successful development of S-City VT utilising the separate components and communicating sustainability through the use of a range visualisation techniques fulfils the third project aim. The research hypothesis is supported in terms of showing that it is possible to develop a DST which combines modelling and simulation with a number of visualisation techniques including 3D rendering. Conclusions regarding the effectiveness of the techniques are discussed in the next section.

10.3 Effectiveness and usability testing of S-City VT

The full evaluation of the effectiveness and usability of S-City VT is covered in Chapter 9. The evaluation used a focus group methodology to test the tool, using the case study described in Chapter 3, against a number of sub-hypotheses;

1) Stakeholders will be able to identify the virtual environment as a city or urban environment and the elements of the urban environment under all visualisation techniques.
2) Stakeholders will suggest a preference for the 3D visualisation over existing methods of sustainability assessment and displaying urban environments.
3) Stakeholders will be able to discriminate which of the two scenarios presented using the split screen system is the more sustainable.

4) Stakeholders will be able to identify the indicator causing the difference in sustainability.
5) Stakeholders will be able to rank buildings in order of sustainability.
6) Different stakeholders will have a preference for different visualisation techniques.
7) Stakeholders can use the DST to determine the sustainability of a real scenario using a number of the visualisation techniques.
8) The Visual DST will encourage engagement and facilitate discussion around the decisions being made.

The results of the focus group sessions showed that S-City VT supported many but not all of the test hypotheses.

Hypotheses 1 was fully supported by the evaluation tests, which shows that S City-VT can create a virtual representation of a recognisable urban environment or city. Including background buildings and surrounding landscape together with noticeable landmarks S-City VT provides the context that has been lacking in other tools which attempt to use virtual environments to communicate sustainability.

Hypothesis 2 was not fully supported by the evaluation test as the groups did not suggest any current sustainability assessment methods that they currently used. However the groups did compare the S-City VT tool with current methods they used for displaying environments and all groups suggested that 3D did provide a number of benefits which would not be possible using their current tools. It was clear that some of the groups had had difficulty in the past using maps and GIS to explain developments to non-expert stakeholders. The non-expert stakeholders themselves commented on how much easier a 3D representation was to grasp, in terms of appearance and scale. It was also clear that the groups felt that using 3D virtual environments would increase the engagement with the tool, especially amongst the younger generation who it was felt were not sufficiently included in decisions and would appreciate techniques, similar to those in the games industry, being used.

Hypotheses 3 & 4 were supported by the evaluation but with some provisos, namely that to identify the most sustainable scenario, the difference between the sustainability index should be greater than 2% and that to identify a single indicator using the weave technique, the difference should be greater than 20%. This shows that S-City VT does provide the user with the ability to choose between scenarios based on their relative sustainability, supporting the decisions being made. The 20% difference identified as the lowest difference at which a single indicator could be identified depended heavily on the amount of discussion with in the group. This value stemmed from a group where little discussion took place and which seemed to be dominated by one participant, which entails that the actual minimum value at which single indicators can be identified using the weave technique could be much lower.

Hypothesis 5 was not supported by the evaluation focus groups. This shows that currently S-City VT does not provide the user with the ability to rank a number of buildings within a development. However, the users were able to identify the least and most sustainable building within the development but were unable to determine a rank for buildings with small sustainability index difference between this maximum and minimum.

Hypothesis 6 was also not supported by the evaluation. It was believed that expert stakeholders would have a preference for obtaining the separate indicator data and basing their decision on these values, however all of the focus groups, expert and non-expert, expressed a preference for the blend technique when judging the relative sustainability of the presented scenarios. Some of the groups did acknowledge that the weave technique was useful in identifying separate indicators and one group performed extremely well at this task. This, combined with the fact that one group did prefer using a different colour scale for the blend technique, than the other groups, shows how important it is that S-City VT provides a range of techniques which the user can choose based on their own preferences.

Hypothesis 7 was not fully supported by the evaluation as some groups were not able to determine the differences between the scenarios and not able to identify all the indicators causing the differences. It is believed that two of the groups were unable to select the most sustainable scenario due to a confusion surrounding the blend scales. In a real world situation the stakeholders would not perform the initial comparison tests which caused the initial confusion and the group facilitator would be able to highlight the colour scales being used more fully; also not all groups had difficulty in performing this task. These findings suggests that S-City VT does have the potential to fully support this hypothesis should the confusion between the colour scales used in the weave and blend techniques be removed by changing the order in which the tests were performed.

Hypothesis 8 is supported by the evaluation as it is clear from the observations and transcriptions taken during the focus groups that by far the highest proportion and most engaging part of each session was spent discussing the decisions being made. It is also evident that those groups where most discussion occurred performed best in the scenario choice tasks using the visualisation techniques and also that these groups, through their discussions, were able to guide each other to the correct choice. The observations taken throughout the focus groups showed that even the most resistant group still became engaged in the decisions being made because of the way in which it was presented even if this engagement only lasted for short periods. As shown in Chapter 7, the ability of the tool to engage stakeholders was further demonstrated at a number of public events, such as the Dundee City Science Festival, where it was also clear that the public were interested in the designs for the waterfront development and had never seen the plans in a way they could engage with before.

10.4 Conclusion of the validity of the overall hypothesis

The overall hypothesis of the thesis is:

Can 3D visualisation and modelling be combined into a single decision support tool to effectively support the decision making process and engage both expert and non-expert stakeholders in the development of sustainable urban environments?

Chapter 2 clearly shows that there is no tool which effectively models and communicates sustainability and supports sustainable decision making in urban environments. Chapters 4-8 show that it was possible to combine 3D visualisation with traditional modelling to create a DST capable of both modelling sustainability and demonstrating the output of these models in a novel way. Chapter 9 shows that in many ways the tool is effective and fulfils the task it was designed for. It should however be acknowledged that there are some areas, namely confusion over some of the colour scales and the ability to rank buildings within a single scenario, which need modified for the hypothesis to be accepted in full.

It is not possible to say definitively that S-City VT is accessible by “all” stakeholders as it was not possible to demonstrate the tool to every person involved. However from the focus group evaluation of S-City VT, it was clear that the tool did provoke discussion and engage all the participants involved in the groups. As the groups were composed of participants from a wide range of expert and non-expert groups, it would suggest that the tool would be accepted by many stakeholders.

It can therefore be concluded that the research hypothesis can be accepted and therefore that 3D visualisation and modelling can be combined into a single decision support tool, which effectively supports the decision making process and engages both expert and non-expert stakeholders in the development of sustainable urban environments.

10.5 Further & associated work

As has been highlighted S-City VT has been designed in a way which makes it as flexible as possible so that even though it was initially designed for the Dundee Waterfront, it can be applied to any urban development. One of the drawbacks of the Dundee Waterfront case study is that the actual layout of the building plots had already been designed before this research was started. This meant there was no opportunity to test how the tool could be used during the master planning stage. Therefore it is felt that the tool should be demonstrated on a project from its very early stages before any decisions have been made. This process has already been started as S-City VT is in the process of being modified for its application to the Dunfermline Western Edge settlement plan which will allows S-City VTs abilities and sustainability assessment and decision making engagement to be tested at very early project stages.

The flexibility of S-City VT is also highlighted by its application to domains other than urban sustainability. The system has already been modified to address the economic, social and environmental costs of managing phosphate levels in rivers as part of a UK Water Industry Research (UKWIR) project, details of this application are available in Appendix 4. The tool is also in the process of being applied to a coastal management project which will attempt to visualise a wide range of factors, including biodiversity, sediment movement, sand dune erosion and flooding, affecting the eastern coast of Fife in Scotland. The use of the tool at a number of public events has also highlighted to Dundee City Council the benefits of the S-City VT tool and it is hoped it can be applied to future developments within the city.

Whilst it was felt there was enough evidence to accept the research hypothesis it was noted that there was one area in which the tool did not fully accomplish its aims, and that this should be addressed in future work. More research should therefore be performed to determine why the users found it difficult to rank a number of buildings in the same scenario.

One other area which should be developed more is the provision for group decision making. S-City VT has been designed for a single person, or groups to use together at one time; it is also possible for users to save designs or scenarios and pass these on to others, however it is not possible for two stakeholders or stakeholder groups to work on the same design from separate locations. To overcome this, S-City VTs future development will determine if it is feasible to utilise computer networking techniques to create a multi-user application via the Internet.

As S-City VT is being applied to other areas, and even different domains other than urban sustainability, it will continue to be refined and updated to ensure it still provides the highest levels of engagement and interactivity to effectively support the decisions being made.

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Appendices

Appendix 1 Detailed Focus Group Analysis

A1.1 **Group 1**

Section 1 General Questions

The group were able to clearly identify the city being represented as Dundee although some of the group would have been given background information to enable them to decide to attend the group which may have suggested the case study being used. However it was clear that he a participants recognised the virtual environment as an urban landscape. The group suggested that the 3D representation was useful as it provided a context for the proposed development where people using the system could get an idea of how high the development would sit and how it would fit with what was already built and developed. It was also suggested that the technology being used would be beneficial as many people are familiar with its use in computer games etc. The group suggested two main methods of viewing urban developments that were usually used in their departments, maps and physical models. Maps were described as being mainly used but not accessible to member of the public in terms of determining what's actually going to be developed. Physical models have and can be used but this practice isn't common due to the high cost, both time and economic, in developing these models for large areas.

Section 2 results of tests on the effectiveness of display techniques.

The group showed suggested a number of landmarks that they recognised including the Discovery, Discovery Point Centre , the Tay Bridge, the Law hill and the war memorial on top of the Law hill showing that they recognised the virtual environment as Dundee. The group were able to identify the elements of the virtual environment while using blend, the weave and with no data view, they were also quite clear that they could identify the boundaries between the elements using any of the possible views. It isn't clear from the transcription or notes whether the group were able to identify the building materials used in the development, this question may have been accidentally omitted by the moderator.

The group were able to identify the most and least sustainable buildings from the scenario given using the both the weave and blend techniques although many of the group members suggested that using the weave method for this task was much harder. Neither method was deemed suitable by the group for ranking the buildings as they were unable, using either method, to positively identify the difference between the remaining three buildings in the scenario.

Blend Results

Test Blend	Chosen Scenario	Actual Scenario	Actual %Difference
1	2	2	80
2	1	1	100
3	1	1	10
4	2	2	8
5	1	1	4
6	2	2	20
7	1	1	40
8	1	1	2
9	0	0	0
10	2	2	6
11	2	2	60

Table A1.1 results of comparisons using the blend technique

The blend results show that the group were extremely adept in identifying the differences between the scenarios getting 100% of the scenarios correct. It was also noted at the meeting that he group were extremely quick in their identification of the scenarios, although there was more discussion over test 9 where the scenarios are the same. This group preferred the red-blue scale.

Weave Results

Test Weave	Chosen Scenario	Chosen Indicator	Actual Scenario	Actual Indicator	Actual %Difference
1	2	hou	2	100	hou
2	2	tou	2	80	tou
3	2	hou	2	20	hou
4	2	eco	2	40	eco
5	0		0	0	#N/A
6	2	eco	2	4	eco
7	2	eng	2	8	eng
8	1	air	1	6	air
9	1	eco	1	60	eco
10	2	eng	2	2	eng
11	1	hou	1	10	hou

Table A1.2 results of comparisons using the weave technique

Similarly the group were able to correctly identify all the scenarios correctly although most participants did suggest that the weave method was much more difficult and there was much more discussion within the group about each scenario and the colours involved before arriving at a decision. The group preferred a mid-range pixel size for the weave test it was also noted that the group picked up the ability to use the weave test very quickly.

Section 3 Choice comparison based on realistic scenario decision

Using the blend technique the group were able to quickly and correctly identify scenario 1 as being the most sustainable. On switching to the weave technique the group entered a discussion about which indicators were different between the two options.

Indicator	Scenario 1 (Mixed Use)	Scenario 2 (Predominately commercial)
Housing	better	worse
Economic Output	worse	better
Noise Pollution	not mentioned	
Energy Efficiency	mentioned	
Employment	not mentioned	
Social Acceptability	better	worse

Table A1.3 results of the choice comparison for the realistic scenario

The group correctly identified some of the indicators which were having an effect on the scenario. Housing provision and social acceptability were correctly identified as being better and economic output as worse in the mixed use scenario and vice versa in the predominantly commercial scenario. The group mentioned that energy efficiency was involved but it was not clear which scenario they thought it was higher or lower in, the group made no mention of Noise Pollution, although it would remain the same across the scenarios, and employment which would be slightly higher in the mixed use scenario.

Identified Themes

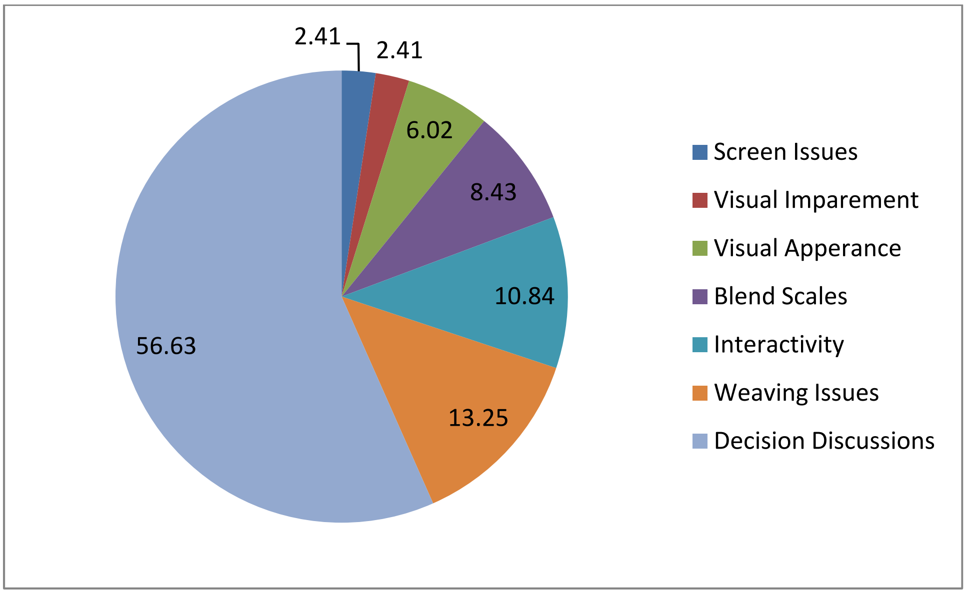


Figure A1.1 Graph showing percentage of themed discussion references recorded from focus group 1

The group mentioned two main issues to do with the screen, which they felt impacted on their ability to identify the scenarios. They felt the screen was too shiny and that the angle the viewer was to the screen affected the colour they saw. These were only an issues when the values were very close and affected both the blend and weave techniques.

Visual Impairment

It was observed by one member of the group that the weave system relied on people to be able to distinguish a quite high level of detail, and suggested that that technique in particular would not work well with someone who had any kind of visual impairment. One of the group members happened to be colour blind, however this was only mentioned quite late in the study. During a close weave comparison the group member was unable to determine the colour that had changed although they were able to tell which scenario was the more sustainable. This visual impairment did not seem to affect the colour blend tests.

Visual Appearance

The group mainly commented that they liked that the visualisation represented a whole development and as such provided the user with the ability to see how the proposed development would look in context. One negative aspect that they mentioned was that during the blend and weave tests the colour of the water is too bright or too blue and they found this distracting.

Blend Scales

Most of the group stated that they liked the red blue scale the best and there was no disagreement from the other members, it was this scale that the group used for the main blend tests. One group member expressed dislike for the burnt orange scale. One group member found changing from the blend to the weave confusing, suggesting that on the "weave scale low sustainability is strongest and it fades out whereas you seem to get darker here at higher sustainability" referring to the red-blue scale where a building with high sustainability will be dark blue. This confusion over dark-light vs. high-low sustainability was also suggested by a group member asking the others "so it stays paler or something" when they were having trouble identifying the most sustainable option using the weave method. Another member suggested that "I think if there was any confusion John having the weave at that size makes it very obvious" and that they thought "most people would probably be ok with [it] and see the difference".

Interactivity

This group extensively asked for the virtual environment to be zoomed in and out during the test when they were having trouble identifying a specific detail. It was also suggested by the group that "the ability to zoom in is important because if people don't have very good vision is could be really difficult to pick out that detail" and that "if you were having difficulty distinguishing you could actually move about" to enable a better understanding of what was being shown.

Weaving Issues

The group found the weaving technique difficult especially in determining which indicator was affecting the scenarios; this can be seen from the proportion of references that were made to weaving issues throughout the focus group (Figure A1.1). They suggested some reasons for this difficulty such as the key was positioned over part of scenario 1 and this could distract from the indicator colours on the weave. They thought that the arrangement of some of the colours, especially the turquoise and the green being beside each other made it harder to recognise a single indicator change.

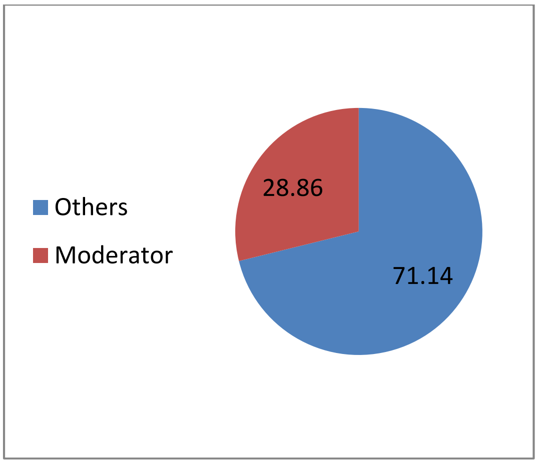
When the scenarios became extremely close many of the group expressed that in a real world situation, they would want to see more information, such as bringing up one of the graphs or looking at the raw data before making a decision. One member suggested that when the scenarios were very close the user may find a difference when there isn't one, stating "that you start really focusing and looking for a difference and that will just be trying too hard".

During the testing to try and overcome the difficulty in the of the weave technique the group developed a method for identifying the differences between the scenarios. The group used a system where they identified identical bits of the pattern, specific shapes in the pattern like T or an L and then were able to determine if the colour was different in this shape.

Decision Discussions

This group demonstrated a high level of interaction when they were deciding on which scenario to choose as the most sustainable nearly all of the decisions made by the group came after some discussion where each member made sure they agreed with the decision, as can be seen in Figure A1.1, this is highlighted by the high proportion of the coded references counted for this theme, nearly four times that of the closest other themes.

Group Dynamic



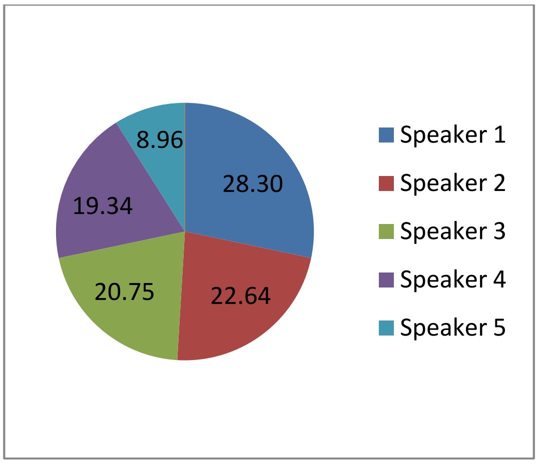


Figure A1.2 Graph showing proportion of references assigned to moderator and other speakers

Figure A1.3 Graph showing proportion of references to focus group participants

Figure A1.2 shows that the from the coded references the moderator was required to speak for about 28% of the time to facilitate the discussion between the group, this time included the introduction and the prompting of the directed questions. This implies that the group were engaging with the moderator and did not need prompted to discuss the scenarios or the questions being asked. The proportion of references applied to each participant in the focus group is shown in Figure A1.3, this shows that no group member in particular controlled the group although one group member (speaker 5) may have not been as engaged.

A1.2 **Group 2**

Section 1 General Questions

The group quickly identified the virtual environment as being "clearly Dundee. Physical models, street elevations, isometrics and cross sections and maps had all been used by members of the group to display urban development's before. The group suggested the prototype would be easier to use than maps as "some people have serious difficulties reading maps, and making the connection between lines and what's actually in the environment". Apart from maps, the group did not directly suggest that it would be easier than the other methods they had mentioned, however it was suggested that some of the existing methods, in particular photomontages submitted with planning applications, have been selectively skewed or "cooked" to provide a positive view of developments that bear little resemblance to the actual developments. The group seemed to like that the prototype provided an unrestricted view so this skewing, especially of aspects such as focal length, would not be as easy to manipulate.

Section 2 results of tests on the effectiveness of display techniques.

The group identified the Law, the Discovery, the bridge and the monument on top of the Law as recognisable landmarks. The group also used the identification specific lines of sight within the virtual environment, using the positions of some of the landmarks to enable their identification of others, for example the identification of the monument was enabled by its alignment to the Tay Road Bridge.

Most members of the group suggested that they would be able to identify the building materials used, or at least that the prototype gave a good representation of what was there but that fine detail would be harder. One member of the group suggested that to identify the building material the user would have to be making "conceptual assumptions” but however also suggested that accuracy and details maybe are not important.

When viewing a range of data the group was able to identify the building with the highest sustainability and the lowest sustainability but were unable to rank the buildings. Using the weave example the group was not able to identify the range of data or the buildings with maximum and minimum sustainability, they suggested that the technique was “harder” and would need “more explanation”. They were able to distinguish between the elements of the scenario whether the scenario was being viewed with either of the visualisation techniques on or off. Although it was suggested by one of the group that it would only be possible to distinguish between the elements of the scenario under the visualisation techniques if the scenario had already been shown without the blend or weave overlay.

Test Blend	Chosen Scenario	Actual Scenario	Actual %Difference
1	1	1	8
2	1	1	6
3	2	2	100
4	2	2	60
5	2	2	20
6	2	2	40
7	2	2	80
8	2	2	10
9	2	2	2
10	0	0	0
11	1	1	4

Table A1.4 results of the comparison using the blend technique

The blend results show that the group were able to correctly identify which of the scenarios was the most sustainable. The group quickly identified some of the scenarios however those scenarios where the values were closer took more time and discussion within the group. One of the group members expressed surprise that potentially, as they did not know the answers at this stage, they were able to identify a difference of 2%. During the blend test, this group predominantly used the red-blue scale during the comparisons.

Test	Chosen		Actual		
Weave	Scenario	Indicator	Scenario	Indicator	%Difference
1	2	acc	2	acc	80
2	2	hou	2	hou	10
3	0		1	air	8
4	2	air	2	air	100
5	0		2	tou	20
6	2	acc	2	acc	60
7	2	acc	2	eco	6
8	1	hou	1	hou	40
9	0		0	#N/A	0
10	1	tou	1	acc	4
11	1	tou	1	tou	2

Table A1.5 results of the comparison using the weave technique

The results of the weave test show that the group found it much more difficult to identify the most sustainable scenario and to identify the indicator affecting the scenario. Even though the group got 36% of the indicator selection wrong they were able to identify the correct scenario for 82% of the comparisons. This group seemed to have difficulty identifying the indicators changing rather than the overall sustainability. The results also show that the group were able to correctly identify the option with equal sustainability indices but also that they falsely identified a difference as much as 20% being equal. This group preferred a larger pixel size for the weave test.

Section 3 Choice comparison based on realistic scenario decision

Scenario 1 was quickly identified, using the blend technique, as being the most sustainable by the group. The weave techniques seemed to provoke more discussion within the group about which indicators were causing the difference between the scenarios.

Indicator	Scenario 1 (Mixed Use)	Scenario 2 (Predominately commercial)
Housing	better	worse
Economic Output	worse	better
Noise Pollution	not mentioned	
Energy Efficiency	worse	better
Employment	not mentioned	
Social Acceptability	better	worse

Table A1.6 indicators identified during the realistic choice comparison

The group correctly identified many of the indicators which were impacting on the scenarios. The group did not discuss Noise Pollution, which as it's based on the building position would be the same in both scenarios or employment which would be slightly higher in mixed use. They did however correctly identify that housing provision and social acceptability were higher in the mixed use scenario and identified that economic output and energy efficiency were better in the predominantly commercial scenario.

Identified Themes

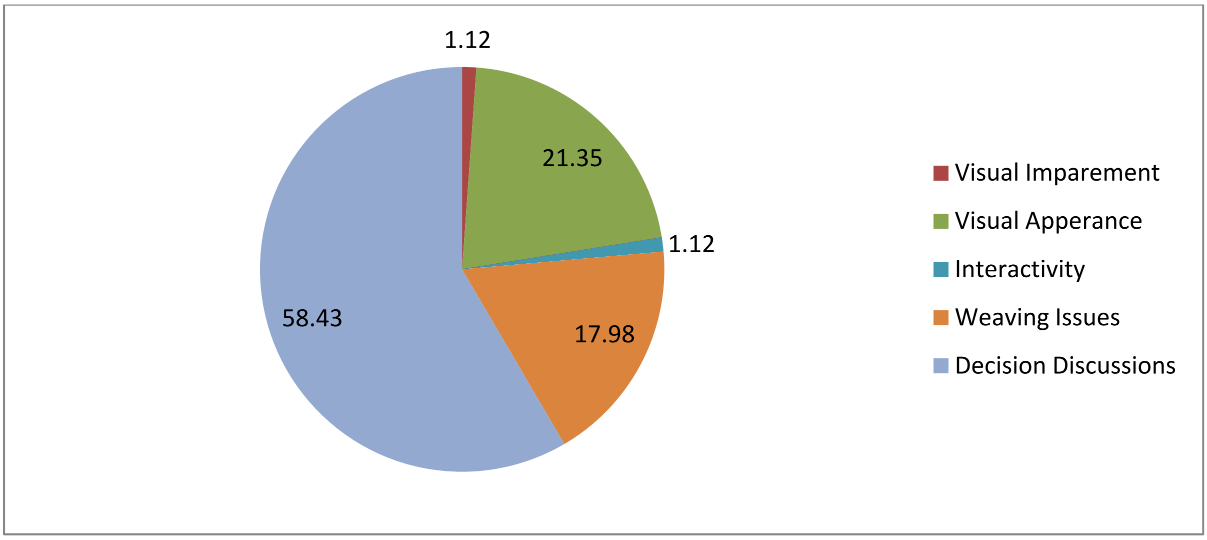


Figure A1.4 Graph showing percentage of themed discussion references recorded from focus group 2

Visual Impairment

One member of the group commented on the fact that one of their bosses was colour blind and that this may affect the viability of the tool.

Visual Appearance

As can be seen from Figure A1.4, the group were concerned about the visual appearance of the visualisation. This was also evident in their discussions about what landmarks they could identify, where the group discussed everything from what hill ranges they could see in the background to whether the monument on the Dundee Law was aligned with the bridge.

The group commented that he visualisation give a sense of scale and context which is not possible with the current methods that they use for demonstrating and planning urban environments. It was also noted that this sense of scale could be enhanced if visual cues were in place to allow a comparison against something of a known fixed height, such as a person.

The group questioned the realism of the virtual environment, suggesting that in parts it was too realistic, "better than real life", due the lack of atmospheric effects. It was suggested by the group that atmospheric effects such as haze or sea haar (coastal fog), which is often present in Dundee, could affect the perceived distances between objects in the city making them seem closer. As the visualisation doesn't contain these effects some of the landmarks may not appear to be the correct distance from each other from certain camera angles. Focal length was also mentioned as something that other techniques, such as photomontages, had used to "skew" or "cook " images and it was asked whether the focal length for the virtual environment was accurate or could be changed.

The group also suggested that the visualisation is "not necessarily meant to be accurate" and that "details maybe aren't important" suggesting that they believed that a representative visualisation was enough.

Interactivity

The group were not overly concerned with the interactivity, as can be seen from Figure A1.4, but they did ask how far the camera could go, i.e. how much of the environment was navigable, and "how far in can we go", demonstrating that they were interested in the camera flexibility.

Weaving Issues

The group found the weaving technique much more difficult than the blending, this is highlighted by the amount of discussion the group had regarding the weaving issues, and this was the second highest referenced discussion in the transcription. The group made many comments about how hard or unsuitable the weaving techniques was in general, suggesting that it would "take a lot more explanation" and the user "could put it into something more suited to your preconceptions". Many of the group made it clear that they were struggling with the weave at different points during the test comments such as "I'm struggling with that", "I can't pick anything out" and "oh God" highlighted the group's difficulty in using the technique.

An optical illusion was noticed by the group where the buildings in one of the scenarios may look bigger than the same buildings in the other scenario. Most of the group members commented on this illusion which only seemed to affect the weave technique and would only occur when the camera was at particular angle.

Some alternatives to the weave method were suggested, such as adding a key which blocks the scales into percentiles or a marker or actual percentage figure on the scale showing where each scenario is allow the user to better identify the most sustainable scenario. Another suggestion was the addition of a bar chart which would allow you to see the colour for a specific percentage, again allowing a better comparison with the weave pixels.

Some members of the group seemed to develop a methods for helping identify the changes during the weave technique testing, it was suggested that it was easier if the colour comparison was based on two blocks.

Decision Discussions

As can be seen from Figure A1.4, this group maintained a high level of engagement throughout the focus group. The amount of references to discussions about the colour or sustainability of a particular scenario outweighs the next nearest theme by nearly three times.

Group Dynamic

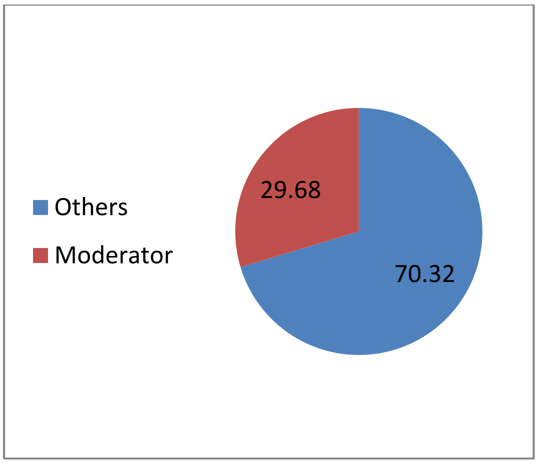


Figure A1.5 Graph showing proportion of references assigned to moderator and other speakers

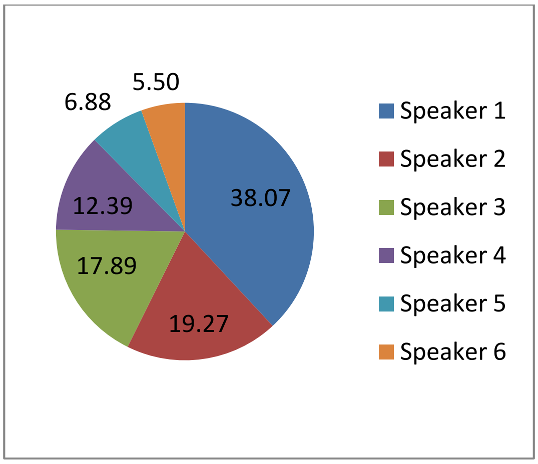


Figure A1.6 Graph showing proportion of references to focus group participants

From Figure A1.5 it can be seen that the moderator had to speak for just under 30% of the time in order to ensure the group were engaged in the discussions, this included asking the direct questions and any introduction and closing remark. Figure A1.6 shows that of the six participants in this focus group speaker 1 seems to have somewhat dominated the group, having almost double the amount of coder references. Two speakers seem to have not been fully engaged in the process having only 5% or 6% of the total references in the focus group. This implies that the group's results may lean towards the feelings and decisions of speaker 1 and not fully reflect the feelings of the group.

A1.3 **Group 3**

Section 1 General Questions

The group quickly identified the virtual environment as Dundee; one member asked where the background data or Dundee had come from before being asked by the moderator what city was being represented. The group suggested that they would find the 3D visualisation useful, especially when doing public consultation, as it gives you an idea of scales, spaces and heights that would be harder to understand from a 2d map. It was also suggested that it gives an indication of how the development all fits together and the relationship between what is being built, what is being developed and what already exists.

The members of the group suggested that they mainly use GIS in displaying urban environments although they do use a system called pictometery which is describes a photographs from an oblique angle which give a detailed representation of existing buildings. When asked how the 3d visualisation compared to these existing system one of the group member contrasted how pictometery provides a detailed view of existing developments where as S-City VT provides a representative view of possible developments. It was also expressed that they would not have any current ability to provide any representation that gave the unrestricted view available in S-City VT and especially allowing people to see developments from eye level was a real advantage.

Section 2 results of tests on the effectiveness of display techniques.

The ship (presumably the Discovery) was the only landmark suggested by the group as a landmark even though it was clear from the discussions that they recognised the virtual development as Dundee, it may have been the case that they believed the question trivial. When shown the different building materials the group suggested that they would be able to make a guess at what the different materials were although they would need more detail and the camera had to be quite close to the building before an identification could be made.

The group were confident in being able to identify the elements of the environment under all the visualisation techniques. They did however have difficultly using the blend and weave techniques to identify the range of data. The blend technique was successful at allowing the group to identify the building with the highest sustainability and the lowest sustainability but they were unable to rank the buildings. The group found the weave technique so difficult to determine that they could neither identify the building with the highest sustainability nor the range of data present.

Test Blend	Chosen Scenario	Actual Scenario	Actual %Difference
1	1	1	4
2	1	1	100
3	0	0	0
4	1	1	60
5	2	2	6
6	1	1	2
7	2	2	8
8	2	2	10
9	2	2	80
10	2	2	20
11	2	2	40

Table A1.7 results of the comparison using the blend technique

The blend comparison results show that the group were able to identify the scenario with the highest sustainability for all the comparison options. It was observed by the not taker that the participants were quickly able to identify the scenarios they were choosing. There was more discussion over test 3 where one of the groups suggested that scenario 2 was more sustainable however the group finally went with the scenarios being the same. The group predominantly used the red-blue scale, however during test 5 the group asked that the scale be changed to greyscale so they could confirm their choice.

Test	Chosen		Actual		
Weave	Scenario	Indicator	Scenario	Indicator	%Difference
1	1	tou	1	tou	80
2	0		1	eco	4
3	2	tou	2	tou	40
4	0		0	#N/A	0
5	1	acc	1	acc	10
6	1	acc	1	acc	20
7	0		1	tou	8
8	0		2	tou	2
9	1	eco	1	eco	100
10	1	eco	1	eco	6
11	1	hou	1	hou	60

Table A1.8 results of the comparison using the weave technique

The results of the weave comparisons show that the group were able to identify the correct scenario in 73% of the presented options. The group correctly identified when the scenarios had the same sustainability index but falsely identified three other scenarios as having equal sustainability indices. It was noted that the group discussed their decisions before choosing.

Section 3 Choice comparison based on realistic scenario decision

One group member quickly identified scenario 1 as being the most sustainable; this was agreed with by the rest of the group. Again the weave techniques produced more discussion before the group arrived at their final decision about which indicators were involved in the scenarios.

Indicator	Scenario 1 (Mixed Use)	Scenario 2 (Predominately commercial)
Housing	better	worse
Economic Output	worse	better
Noise Pollution	not mentioned	
Energy Efficiency	worse	better
Employment	marginally better	marginally worse

Table A1.9 indicators identified during the realistic choice comparison

The group correctly identified all the indicators that were different between the two scenarios. Housing provision and social acceptability were identified as being higher and employment as slightly higher in scenario 1, economic output and energy efficiency as higher in scenario 2. The group did not mention Noise Pollution, which would be the same across both scenarios, this may be because they were identifying the indicators which changed and not those that stayed the same.

Identified Themes

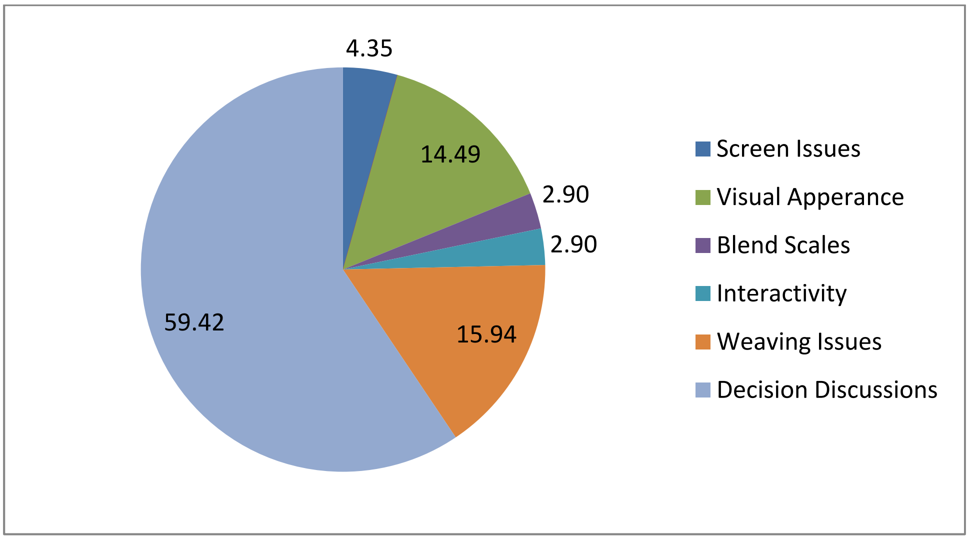


Figure A1.7 Graph showing percentage of themed discussion recorded from focus group 3

Screen Issues

There were two issues with the screen being used for the focus group which the group felt may have affected their ability to discriminate between the scenarios. It was mentioned that one members blue shirt may have been reflecting in the screen causing a problem in the identification of the most sustainable method whilst using the blend technique. It was also suggested by the group that the colours being shown changed depending on the viewer's angle to the screen and again this could determine how the sustainability of a certain scenario was viewed. Both of these effects only occurred when the values were close together, <10%.

Visual Appearance

The group suggested that the visualisation made the environment more realistic by providing the viewer with a sense of scale and spaces. They thought that it would be much easier for someone to understand what is going to be built than a 2d representation that they would have to think much longer about.

The realism of the virtual environment was discussed by the group and a number of question were asked about the validity of the background data, in particular the accuracy of the lidar data and whether it had to be manipulated before being added to the visualisation. There were also question about the possibility of applying render to the buildings surrounding the water front so that it looked even more realistic and how long this process would take. Although it was also mentioned that the having the periphery buildings not involved in the decision at a lower detail still provided context for the decision but drew the viewers attention to actual development in question. The group also felt that the textures used to represent the building materials would need more detail if they were to adequately represent specific real life materials.

During the blend and weave tests the group mentioned that the intense blue colour of the cartoon water which is used instead of the realistic water during the blend and weave tests may have an impact on their ability to differentiate between the scenarios and could so affect how the sustainability of the scenarios are viewed.

Blend Scales

The group did not seem to have any major issues with the blend scales or identifying the scenarios using the blend techniques. It was mentioned that the maximum and minimum ends of the red-blue scale are too harsh and quite hard to look at. One group member also suggested that when the scales were changed to determine if the group preferred a different colour scale, that it took a few moments to get used to the new scale.

Interactivity

Even though the interactivity did not play a large part in the discussions, the ability to move around the environment at will was noted as being important as at the minute the groups department would have nothing that would let them perform dynamic walkthroughs or let you see a proposed development from unrestricted camera views. The zoom was also mentioned as being important when the group were attempting to determine the building materials used on the development.

Weaving Issues

The group expressed difficulties in determining the relative sustainability of the scenarios using the weave technique, mainly they seemed to find it too complicated, “very difficult” and “too busy”, one member found it extremely hard to concentrate on making the decisions, their comment “I have to say that I've switched off, I can’t concentrate enough to make it out” highlights this feeling. Some of the group did persevere and suggested a technique that would help identify the differences between the scenarios suggesting that the group “look at the pattern, take a corner and look at it”. When the sustainability of the scenarios got very close together the group stated that if it was that close they would want to look at the data.

Alternatives to the weave techniques were also proposed including having simple bars or chunks drawn on the buildings demonstrating the sustainability. It is not clear from the group’s reaction to the reasoning of the use of the weave technique whether or not they agreed with it.

The group also noticed an optical illusion where one of the buildings in one of the scenarios looked bigger than its corresponding building in the opposite scenario. This only occurred during the weave tests and only at specific camera angles.

Decision Discussions

The high proportion, just under 4 times that of the nearest other theme, of the references to discussions about the sustainability decisions seems to show that in most cases the group were provoked to discuss what it was they were seeing before they made a final decision.

Group Dynamic

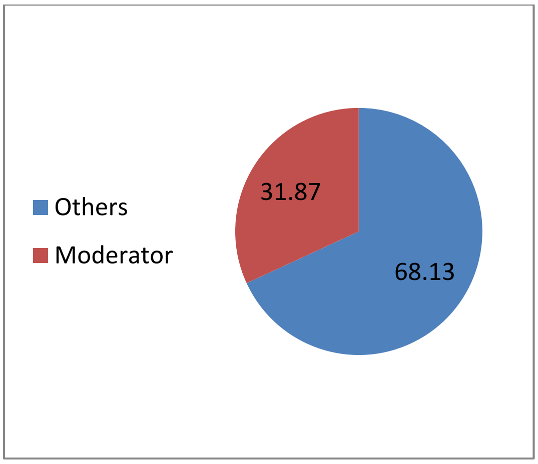


Figure A1.8 Graph showing proportion of references assigned to moderator and other speakers

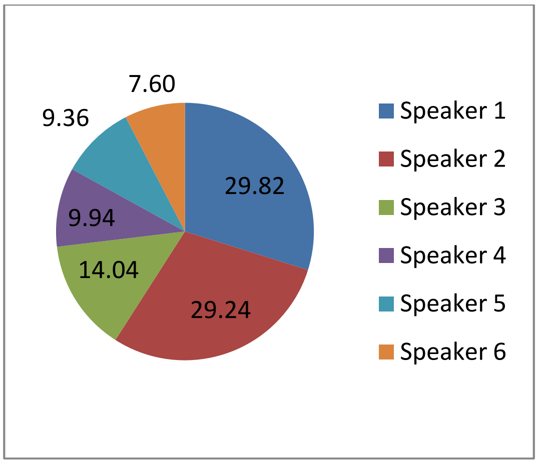


Figure A1.9 Graph showing proportion of references to focus group participants

Figure A1.8 shows that the moderator was assigned just over 30% of the all the speaker references for the focus group, this implies that the moderator did not excessively need to prompt the participants in their answers to the questions or overly facilitate their discussions about their decisions.

Figure A1.9 shows that the proportions of the references assigned to the different speakers suggest that the participants engaged with the focus group to different degrees. There is not one single group member who stands out as dominating the group; however two members seem to have spoken more than the others. However it was observed by the note taker that during the focus group that all the participants were engaged in the process, the speakers could simply have agreed with what was being said by the other members.

A1.4 **Group 4**

Section 1 General Questions

The virtual environment was described as being very recognisable, although the group didn't specify what city they thought it was, they did identify "the waterfront and where the Discovery is" implying that they recognised the city as Dundee. They thought the 3D visualisation was important as it would let people look at the parts of the development that they wanted to, and that the 3D provided a much better "way of doing it than bits of paper or even the sort of models you get (sic)" . The group suggested that the technology used could provide a way of engaging young people in the community, something that they have always struggled with, as they will be more used to modern media. It was also suggested that the visualisation gives the idea of height which isn't possible with maps. The group seemed to have been exposed to a range of methods in the past including photomontages, physical models and site visits to explain proposed developments. The group suggested that S-City VT incorporated all of these aspects allowing the users to compare what is there visually and to apply effects such as traffic and weather.

Section 2 results of tests on the effectiveness of display techniques.

The group said that they were able to identify landmarks in the environment stating the Discovery Point centre as an example. When the group was shown the different building material they were able to tell "that's glass and that's brick" however they did feel that the distance the buildings were from the camera made a difference.

The elements of the virtual environment were recognisable to the group in all off the visualisation techniques. The group was also able to identify the buildings with maximum sustainability and minimum sustainability using the blend technique however they found that the weave technique more difficult with “a wee bit too much detail”.

Test Blend	Chosen Scenario	Actual Scenario	Actual %Difference
1	2	2	80
2	1	1	6
3	1	1	10
4	0	0	0
5	1	1	4
6	1	1	2
7	1	1	40
8	1	1	8
9	2	2	100
10	2	2	60
11	2	2	20

Table A1.10 results of the comparison using the blend technique

The blend comparison results show that the group were able to correctly identify the scenario with the highest sustainability in all the comparisons shown, it also shows that they were able to determine when the scenarios had the same sustainability indicator. The notes taken at the focus group also show that for many of the comparisons the group were very quick, after some small discussion, in deciding which scenario to choose. The closer the scenarios sustainability indexes the more discussion took place with the exception of the identical scenario where the decision was relatively quick.

Test	Chosen		Actual		
Weave	Scenario	Indicator	Scenario	Indicator	%Difference
1	1	eng	1	eng	20
2	2	acc	2	acc	80
3	2	eng	2	eng	6
4	1	eng	1	eng	10
5	1	air	1	air	40
6	0		0	#N/A	0
7	1		1	acc	2
8	2	acc	2	acc	8
9	2	eng	2	eng	4
10	1	tou	1	tou	60
11	2	eng	2	eng	100

Table A1.11 results of the comparison using the weave technique

The weave comparison results show that the group identified the scenario with the highest sustainability for 100% of the given options, however they were not always able to identify which indicator was affecting the sustainability of the scenarios. At the 2% level the group were able to identify which scenario was the most sustainable but not that it was social acceptability (yellow) which was determining this level. From the notes taken at the focus group it was recorded that for most of the decision there was a relatively large amount of discussion compared to the blend comparisons.

Section 3 Choice comparison based on realistic scenario decision

The group wrongly identified scenario 2 as the most sustainable, suggesting this was the case because it was lighter. With the weave technique the group attempted to identify the differences in the scenarios.

Indicator	Scenario 1 (Mixed Use)	Scenario 2 (Predominately commercial)
Housing	not mentioned	
Economic Output	not mentioned	
Noise Pollution	mentioned	
Energy Efficiency	mentioned	
Employment	not mentioned	

Table A1.12 indicators identified during the realistic choice comparison

The group correctly identified that the energy efficiency between the two scenarios is different; however the group also identified Noise Pollution as having different levels, which is not the case as the Noise Pollution will remain constant across the scenarios. A number of indicators were not mentioned by the group, housing provision, economic output; employment and social acceptability, all of these indicators have different levels on the two scenarios shown.

Identified Themes

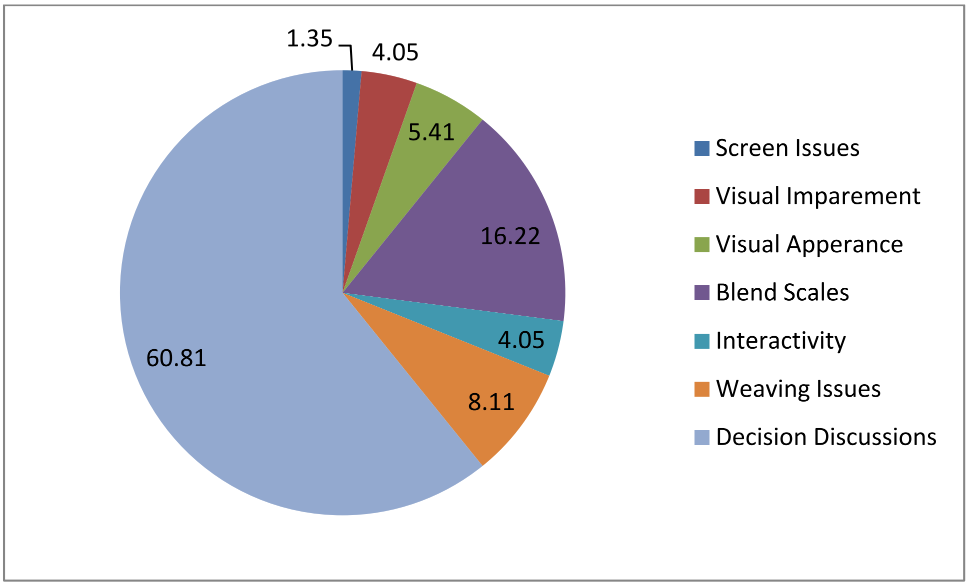


Figure A1.10 Graph showing percentage of themed discussion recorded from focus group 4

Screen Issues

The group had some slight issues with the screen, commenting that the angle the viewer was to the screen affected the colour seen and would in turn affect how the sustainability of the scenario was decided upon.

Visual Impairment

The group did not expressly mention visual impairment as an issue until it became quite clear to the group that one member was not seeing the same colours as the rest of them. This particular participant couldn't understand why the moderator and the other group members were describing the red-blue scale as red-blue when the participant was detecting shades of red as green. This did not seem to have an effect on the participant being able to choose the more sustainable scenario using the blend scale, however not being able to describe the colour in the same way as the other participants seemed to irritate the participant although they were more than happy to continue. During the course of the focus group it was noticed that this could also have been an effect of the screen angle.

Visual Appearance

The group stated that the virtual environment was "very recognisable" and were able to identify a number of landmarks which they recognised. It was mentioned that the virtual environment coupled with effects like the weather and traffic would let someone see how a new development would look under different situations and provide a context of how it would fit with what was already there.

Blend Scales

The group had a few issues with the blend scales used in the visualisation. Mainly this seemed to be caused by confusion over the colour maps. The participants seemed to lose where in the colour map a particular colour sat and so were able to tell if a scenario was lighter or darker but were then unable to tell if this mapped to a higher or lower sustainability. The group thought that for them the gray scale was the best for determining the difference between the scenarios, and this was the scale that was predominantly used for the focus group blend tests. However on a number of occasions the participants asked why the scale had changed from dark meaning low sustainability and light meaning high sustainability, when in actual fact the scale hadn't changed whilst using the gray-scale for the blend test and during the weave tests the lighter a colour always represents a higher sustainability. This particular participant asked this question for every scenario comparison and seemed unable to identity each time which colour linked to which level of sustainability. It is possible that there was some confusion between the scales used for the weave and the possible scales for the blend test, especially the red-blue scale, which even though was not used by the group was available on a hand out in front of them, it could also be possible that the key to the current scale on the screen was not clear or visible enough.

Interactivity

The group thought that the interactivity provided by the application would allow for more people, specifically the younger generation, to engage with the planning process. They suggested that the younger generation would be enthusiastic about taking control over the environment and looking around. Whereas the group themselves maybe would not have the confidence to move about the environment, one participant stated that they did "not do technology", but would have the confidence to ask a facilitator to move the view about for them. Although it was also mentioned that someone else controlling the view could be quite disorientating.

Weaving Issues

The group stated quite clearly that they found the weaving technique much harder to use and also that required much more effort to identify the scenarios than the blend methods. Their main issue was the difficulty in identifying what indicator was different between the two scenario choices. One reason for this difficulty was that some of the colours used for the weave technique we more dominant, such as red and blue and that these may washout the less dominant colours cyan/turquoise and yellow. One participant stated that they hadn't even noticed cyan/turquoise until it was at a particularly high level.

Decision Discussions

From the proportion of references counted for this theme it is clear that this group spent by far the biggest proportion of the focus group discussing the decisions they were making. Mainly these discussions revolved around what colour was changing and what scenario was showing the lightest colour, then how this mapped to high or low sustainability.

Group Dynamic

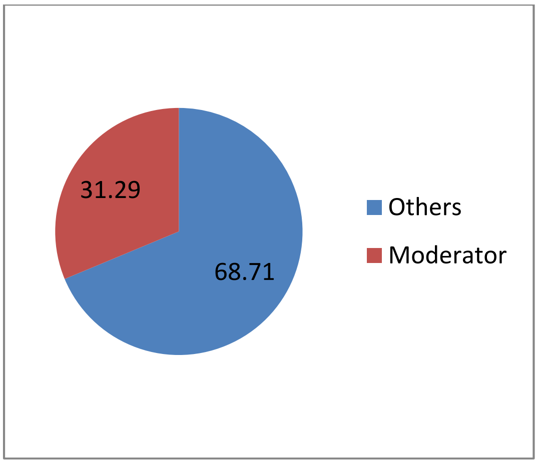


Figure A1.11 Graph showing proportion of references assigned to moderator and other speakers

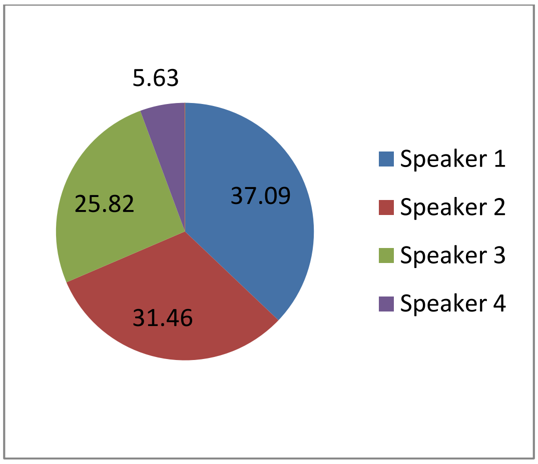


Figure A1.12 Graph showing proportion of references to focus group participants

Figure A1.11 shows that the moderator was assigned just over 30% of the all the speaker references for the focus group. This implies that the moderator did not excessively need to prompt the participants in their answers to the questions or overly facilitate their discussions about their decisions.

The proportions of references assigned to the different speakers Figure A1.12 shows that the engagement in the focus group came largely from three of the speakers who had similar a similar number of references. One speaker, speaker 7 seems to have not fully engaged in the focus group and as such their views may not be reflected in the decisions of the group. However it was observed by the two note takers that all the participants of the focus group seemed to be fully engaged throughout the process. This indicates that speaker 7 voice is possibly not heard on the audio recording or that they were engaged but only spoke when they disagreed with what had already been said.

A1.5 **Group 5**

Section 1 General Questions

The members of this group were involved in the development of the Dundee Waterfront Masterplan and as such had extensive knowledge of the water front and Dundee. They suggested the virtual environment was a “pretty good” representation of the waterfront and that it did resemble an urban landscape. The group suggested that the virtual environment would be more useful than a 2d plan for presentation and consultation. One member of the group expressed a like for the drive through element but also suggested that this was possible with Google SketchUp, however the ability to quickly and easily change the appearance of a building which was confirmed by another group member as not being possible in Google SketchUp was also mentioned as something that particular participant liked. One group member had a particular interest in the control system, previously the member had used Google SketchUp for public consultation but members of the public found the control system too complicated, it was implied that the game like control system in the prototype visualisation would be easier to use.

Section 2 results of tests on the effectiveness of display techniques.

The group identified the “ship” (the Discovery) and the rest of the waterfront as a recognisable landmark when asked, although they had previously mentioned “the bridge” (Tay Road Bridge) and the port area highlighting that they were able to pick out a number of aspects of the virtual environment that they recognised.

The group were able to identify the building materials, however they stated the accuracy with which they could do this depended on “how close you were” from the object in question, but at longer distances you could get “a feel for it”.

The group were able to determine the elements of the environment under the three different visualisation methods. When show the range of data the group were able to pick out the most sustainable building based on its colour using the blend technique, although they did not suggest a rank for the other four buildings. The group found the weave techniques harder, one member said that you could "just pick it out" and that it was possible to see a difference between them, but again it was not clear what building the member was suggesting was the most sustainable or if it were possible for them to rank the buildings in terms of sustainability. Other members of the group expressed that they found the weave "quite difficult" and "not easy to see".

Test Blend	Chosen Scenario	Actual	
		Scenario	%Difference
1	2	2	60
2	2	2	80
3	2	2	100
4	1	1	4
5	1	1	2
6	2	2	20
7	1	1	6
8	0	0	0
9	2	2	40
10	2	2	10
11	1	1	8

Table A1.13 results of the comparison using the blend technique

The results of the blend comparison show that the group were able to correctly identify the scenario with the highest sustainability for all the tests. It was noted that the group were able to perform this quickly although it was noted that it was mainly one or two participants who made the decision and the others agreed.

Test Weave	Chosen		Actual		
	Scenario	Indicator	Scenario	Indicator	%Difference
1	1	air	1	air	100
2	1	acc	1	acc	80
3	2	eng	2	eng	60
4	1	acc	1	acc	40
5	0		2	air	10
6	0		2	eco	2
7	0		0	#N/A	0
8	0		2	hou	8
9	0		1	eng	4
10	1	hou	1	hou	20
11	0	eng	1	eng	6

Table A1.14 results of the comparison using the weave technique

The weave comparison results show that the group had some difficulty in determining small differences in the scenarios. The group were unable to identify the correct scenario for 45% of the tests although for the scenarios they did correctly identify they were able to also identify the indicator which was causing the effect. It was noted that the group seemed to become fatigued with the tests and made their decision very quickly with little discussion, this section of the focus group passed very quickly.

Section 3 Choice comparison based on realistic scenario decision

Two members of the group quickly decided that scenario 2 was the more sustainable because it was lighter. Scenario 2 was not the more sustainable scenario; this may have been a caused by confusion with the colour mapping. Using the weave the group were able to identify some of the indicators involved.

Indicator	Scenario 1 (Mixed Use)	Scenario 2 (Predominately commercial)
Housing	higher	lower
Economic Output	lower	higher
Noise Pollution	not mentioned	
Energy Efficiency	lower	higher
Employment	not mentioned	
Social Acceptability	not mentioned	

Table A1.15 indicators identified during the realistic choice comparison

The group correctly identified that the economic output and energy efficiency were lower and housing provision higher in scenario 1. They did not mention Noise Pollution, which remains constant across the scenarios or employment and social acceptability which will be different.

Identified Themes

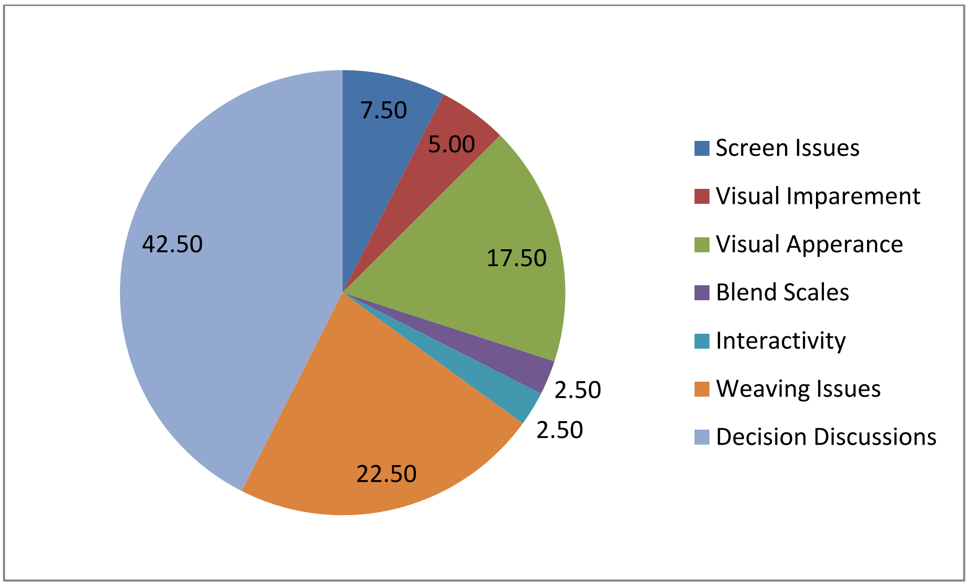


Figure A1.13 Graph showing percentage of themed discussion recorded from focus group 5

Screen Issues

The group made a number of references to the fact that the apparent colour on the screen changed based on the viewer's position or angle to the screen, it was also pointed out that the lighting in the room may be affecting the viewable colours. The group felt both of these aspects may have affected how they decided on which scenario being viewed was the most sustainable.

Visual Impairment

One of the participants asked if the application had been tested for accessibility as they were concerned about its effectiveness in regards to people with visual impairment, the participant was informed that as a prototype the application had not been tested for accessibility. Another member of the group suggested that colour blind may in fact be very good at determining differences in shades of colour.

Visual Appearance

The main aspect of the visual appearance that the group mentioned was that he virtual environment was a "pretty good" representation of the urban environment. It was also suggested by the group that during the weave and blend comparison tests that the colour of the water was too strong and that this could affect their ability to differentiate between the scenarios.

Blend Scales

It was mentioned by the group that it was confusing that the scales changed in meaning, that at some times dark meant low sustainability and light meant high sustainability, again this seemed to come from changing between the red-blue scale to the weave scale.

Interactivity

The group commented on the ability to reset the camera to a default position, one participant thought this was important as when they had attempted to allow participation previously using SketchUp, people had got lost in the virtual environment.

Weaving Issues

The group found that the weave technique required more thinking and didn't find the differences easy to see. They also suggested that the some of the colours would be dominated by others, "particularly with the red and blue". Even for the large differences the group suggested that they would want to know "exactly what's running" and what each individual building was. In the entire group seem reluctant to pick a scenario based on the colours alone.

Some solutions to the difficulty in the weave technique were suggested by the group including viewing the information in lines rather than blocks. Although one member recognised the reasoning behind the weave was to have a display method which functioned irrespective of the building size. Another member suggested that they would want the indicators to be shown separately with a "mechanism to look through all the indicators"; this was mentioned more than one during the focus group.

Decision Discussions

The discussions about the decisions made forms the largest proportion of the coded references recorded for the focus group. These discussions involved the group suggesting and identifying the most sustainable scenario as a group. It was noted by the moderator and by the note taker at the focus group that this group were quite reserved in their discussions about the relative sustainability of each scenario.

Group Dynamic

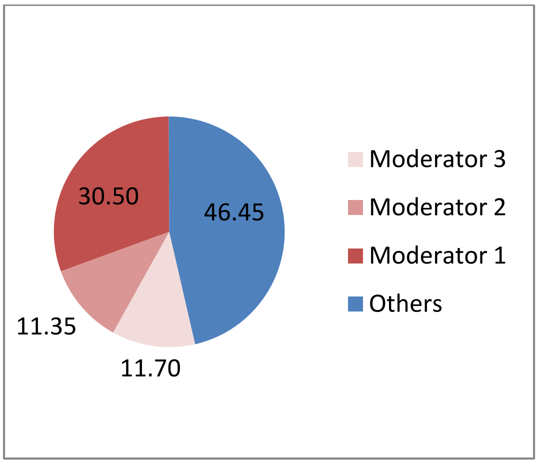


Figure A1.14 Graph showing proportion of references assigned to moderator and other speakers

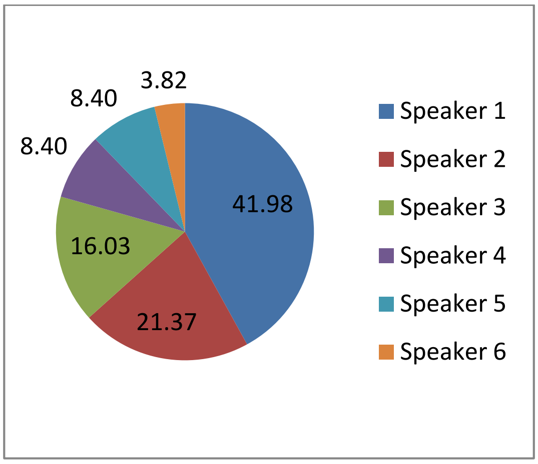


Figure A1.15 Graph showing proportion of references to focus group participants

During focus group 5 it was necessary to take a different approach due to the engagement levels noted by the moderation & note takers. The group seemed reluctant to answer the direct questions and to discuss the decisions about the scenarios. Due to these engagement issues the note takers felt obliged, along with the moderator to attempt to encourage the group into more discussion. This can be seen in Figure A1.14, where Moderator 2 & 3 represent the note takers input into the group. It can be seen by the proportion of references that combined the moderator total over 50% of the total references showing that the prompts and encouragement by the moderation team were quite extensive.

The proportions of references assigned to the different speakers shown in Figure A1.15 show that the group did seem to be dominated by a single participant. Speaker 1 has nearly double the references compared to the next highest referenced speaker that one speaker in particular (speaker6) seems to have had little engagement in the group. It also seems that speaker 6 has had very little engagement with the group. These proportions imply that the results of the focus group may not reflect the feelings and views of the whole group. This was supported by the note takers and the moderator who observed that a kind of hierarchy was in effect where a decision was made by one participant and the others accepted this decision. It was also noted by the moderation team that body language of the group was quite reserved and possibly defensive.

Appendix 2 Original themes identified from focus group analysis

The following table lists the themes identified during the focus group analysis, this set of sub theme was the reduced for the final focus group discussions presented in Chapter 9 and Appendix 1.

Blend Scales	
	Confusion over mapping Light & dark vs High Sustainability & Low Sustainability Orange doesn't look good Prefer Black & White Prefer Red & Blue
Sustainability Discussions	
	Discussion about which scenario to choose
Interactivity	
	User Control Zooming
Other Methods of assessment	
	GIS Maps Photomontage Physical Modelling Pictometery Site Visits Sketchup
Screen Issues	
	Screen Angle Shiny Screen
Visual Appearance	
	Colour of the water Conceptual assumptions Context Realism Realism doesn't matter Recognition of Dundee
Visual Impairment	
	Colour Blindness Sight Impairment
Weaving Issues	
	Alternatives to weaving Colour positions Detection techniques for weaving Difficulty in determining difference Visual illusion caused by weave Would need to see underlying data

Appendix 3 Journal Publications

Appendix 4 PhiZ Visualisation System

Appendix 5 Abridged focus group transcripts (on attached CD)

Appendix 6 S-City VT videos (on attached CD)