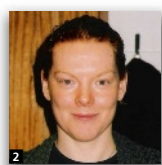
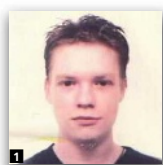


Enhancing urban sustainability using 3D visualisation

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This paper presents the results of an initial application of a prototype simulation and visualisation tool (S-City VT) that was developed to enable all stakeholders, regardless of background or experience, to understand, interact with and influence decisions made on the sustainability of urban design. The tool takes the unique approach of combining three-dimensional (3D) interactive and immersive technologies with computer modelling to present stakeholders with an interactive virtual development. Use of outputs from the model and a 3D visualisation of the development can help decision-makers judge the relative sustainability of different aspects of a development. The tool employs a number of different methods to present sustainability results to stakeholders. Initial tests on the effectiveness of the different visualisation methods are described and discussed. The paper then presents some conclusions on further development and application of the tool to model and visualise possible results of decisions made at different stages of the project.

1. Introduction

One definition of sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs (Brundtland, 1987). It is a vision of progress that integrates immediate and long-term needs and local and global needs, and regards society, environment and economics as inseparable and interdependent. However, for many, sustainable development is often seen as a complex issue that is not definable in practical terms. Although a large body of work has been undertaken to conceptualise sustainable development and there is a growing awareness of it, the real challenge is putting a holistic view of sustainability into practice. Sustainability is an umbrella term that includes all the aspects of social, environmental and economic dimensions.

Sustainable decision-making in urban design is a complex and non-linear (iterative) process that requires the interaction of a wide variety of stakeholders and an understanding of the complex interactions between a large number of sustainability indicators (Foxon, 2002). This is dependent on genuine

stakeholder contribution during the 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). Tools to support the decision-making process are commonplace but are dominated by the perceptions of 'experts' (e.g. planners, architects and design engineers) and focus mainly on the technical design and optioneering stages of the process. Sustainable decision-support tools have been developed (Ashley *et al.*, 2004) but a major barrier to the development and implementation of tools to support urban design is the complexity of the environment in which decisions are made (Bouchart *et al.*, 2002; Hull and Tricker, 2005). In particular, engagement with the general public throughout the decision-making process presents challenges not only in communicating 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. Previous work by Al-Kodmany (2002) has shown that computerised tools enable more participation than traditional methods. Given the complexity of urban design, computerisation

is thus a prerequisite for modern urban sustainable decision tools. Kapelan *et al.* (2005) discussed the state-of-the-art in urban sustainability assessment and decision-support tools, and concluded that although decision-support tools such as Bequest (Bentivegna *et al.*, 2002), Steeds (Brand *et al.*, 2002) and Tresis (Hensher and Ton, 2002) have improved the integration and flexibility of such tools, there is still scope for improvement. Isaacs *et al.* (2007) suggested some of the ways in which their drawbacks could be addressed using visualisation and modelling.

It is therefore believed that there is a need for a new paradigm of decision-support tools that can deal with the complexity of urban design and which go beyond the technical orientation of previous tools (Sahota and Jeffrey, 2005) to enable the real inclusion of valid and measurable indicators of sustainability in decision-making processes. Furthermore, due to the volume of data involved, the key component of such tools is visualisation to aid interaction amongst stakeholders. Visualisation has been used to visualise and analyse changes in the urban design arena (Sembolini *et al.*, 2004; Shellito *et al.*, 2004) and to model the best options for sustainable transport systems (Fedra, 2004). However, none have been used to communicate and integrate the various views of stakeholders in order to enhance sustainable decision-making and stakeholder interaction.

This paper describes an interactive computation and visualisation platform (S-City VT) that integrates and can communicate complex multi-disciplinary information to diverse stakeholder groups, including local authorities and the general public, to enable them to undertake their duties in a way that contributes to the achievement of sustainable development. The tool uses three-dimensional (3D) graphical programming techniques to display an extensive 3D virtual environment, using consumer hardware, by implementing the latest technologies used in the computer games industry in conjunction with an underlying computational model (Isaacs *et al.*, 2008). The prototype was developed with long-term use in mind and therefore the visualisation tool is embedded into a sustainability enhancement framework (Figure 1). A number of visualisation techniques were adopted potentially to satisfy the needs of a wide range of users, thus enhancing the tool's long-term usability. The development is also based on modular software engineering principles, giving the tool the capacity to adapt easily to future requirements and resources (Heeks, 2005). 3D visualisations of a development encapsulate the results of the models and thus the relative sustainability of the development. As mentioned earlier, the tool employs a number of different methods to display the sustainability results to stakeholders. These methods present the data in varying levels of complexity depending on the expertise of the stakeholder, thus empowering all stakeholders by illustrating possible trade-offs between indicator values and sustainability. Eventually, the tool will

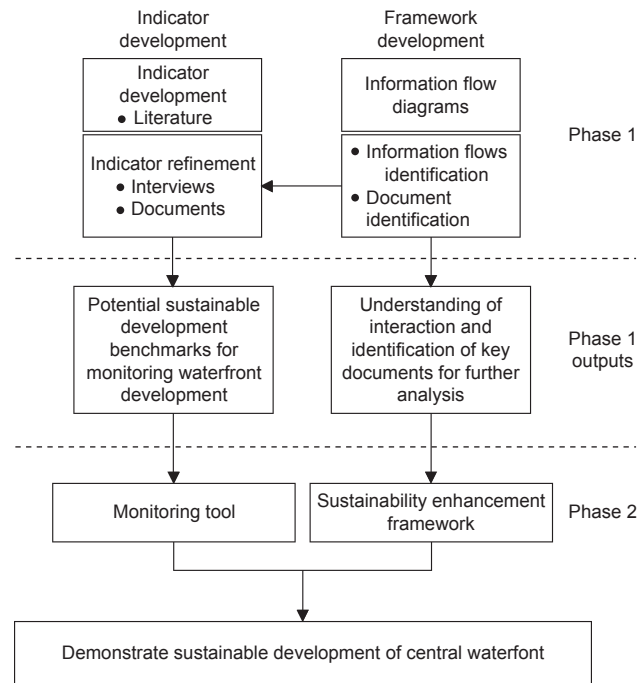


Figure 1. Dundee central waterfront sustainability enhancement study

model and visualise through time the possible results of decisions made that affect indicator values at different stages during project development. This animated simulation will thus allow direct comparisons to be made.

2. Dundee central waterfront development project

Dundee waterfront was largely untouched until 1960 when the council accepted a proposal to build a road bridge connecting Dundee to the Fife coast. Major construction work was carried out on the waterfront area, including 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 council's own offices in Tayside House and the Olympia Leisure Centre) were to form part of a 'multi-level, modernist, civic and commercial centre' (Dundee Waterfront, 2007) that was never completed. These developments left the city, which had at one time been so heavily entwined with the river, completely severed from the waterfront.

As shown in Figure 2, Dundee's population grew exponentially throughout the nineteenth century with the arrival and development of the jute industry. During the first half of the twentieth century, the population gradually tailed off as the

industry collapsed. With declining economy and population, it is possible that Dundee has already become a victim of unsustainable developments.

Due to the scale and importance of proposed central waterfront development, the project steering group was committed to the principles of sustainable development and were conscious of a need to demonstrate this to the Scottish Executive, European funding bodies, private investors and the public. The development work on the tool is part of a larger research programme, in conjunction with Dundee City Council, was thus to develop a sustainability enhancement framework for the Dundee central waterfront project. The elements of the project are shown in Figure 1. The enhancement framework will influence decisions taken at various stages of the waterfront project through the use of indicators established to monitor its sustainable development. Figure 3 outlines how sustainability can be considered at different stages of a project lifecycle. Influencing sustainability at each stage is achieved by embedding sustainable development concepts within existing decision-making and project management procedures and processes (e.g. sustainable issues in risk registers, special requirements for site waste management plans in tender documents).

Information flow mapping was carried out at the beginning of the study (Gilmour *et al.*, 2007) to identify key stakeholders, their roles in the process and the procedures used during decision-making. Decision mapping was undertaken with

- (a) the city engineer, whose team is responsible for delivery of the project
- (b) a Dundee Central Waterfront coordinator, a planner responsible for overall coordination of the project and, in particular, public consultation and liaising with stakeholders
- (c) Scottish Enterprise Tayside (SET).

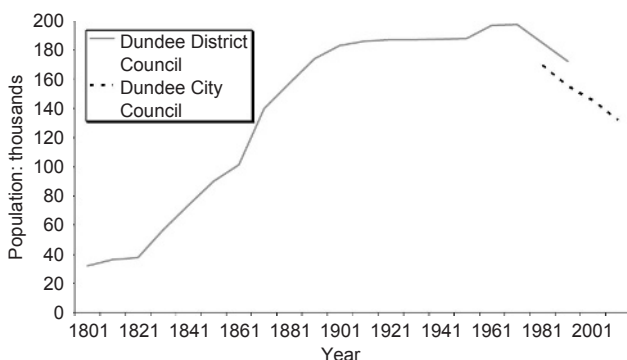


Figure 2. Population change in the Dundee area 1801–2011 (DCC, 2004)

Following these mapping exercises, the researchers were embedded within the Dundee Central Waterfront team to further identify where sustainability could be influenced in the process and to make an assessment of the information needs of the stakeholders.

Indicators were developed to provide a benchmark for identifying, reporting and communicating the sustainable development of Dundee central waterfront. These indicators help to break down the concept of sustainable development to give it a clearer definition and hence make it more comprehensible. Simply put, an indicator is something that helps us understand where we are, which way we are going and how far we are from where we want to be (Simon, 2003). The process of indicator development is iterative and consists of three main activities – literature review, interviews and document analysis. Each policy document and waterfront-specific document that might contain potential sustainability indicators was reviewed and the relevant indicators short-listed. Each indicator on the shortlist was reviewed to identify its appropriateness to the central waterfront in relation to its scale, geographical area, unit of measurement, focus and direction. Indicators were then grouped into one of three categories – economic, environmental and social. A definition for each indicator was then assigned together with draft units. The indicators were designed to align as closely as possible with Scottish government indicators to provide a basis for tangible reporting to the Scottish government, whilst providing clear and easily understood indicators for internal monitoring at the strategic level.

Where Scottish or UK government indicators did not exist, specific indicators were developed based on the authors' experience of sustainable indicator development (Ashley *et al.*, 2002; Butler *et al.*, 2003) and on a range relevant sustainable urban development research papers. Unfortunately, most of the papers reviewed presented a conceptual understanding of the urban environment and identified key components of sustainability (McAllister, 2005) rather than presenting indicators. However, these key components were developed into indicators, which balanced economic, environmental and social aspects of sustainable development. Well-chosen indicators should focus on materiality and accessibility (Olsen, 2004) – materiality concerns the information stakeholders want and accessibility refers to the ability of stakeholders to acquire and understand the information contained in indicators. Indicators should also have the following four characteristics (Foxon, 2002).

- (a) Comprehensiveness. The indicators should cover economic, environmental and social categories in order to ensure that account is being taken of progress towards sustainable development objectives. The indicators chosen need to have the ability to demonstrate movement

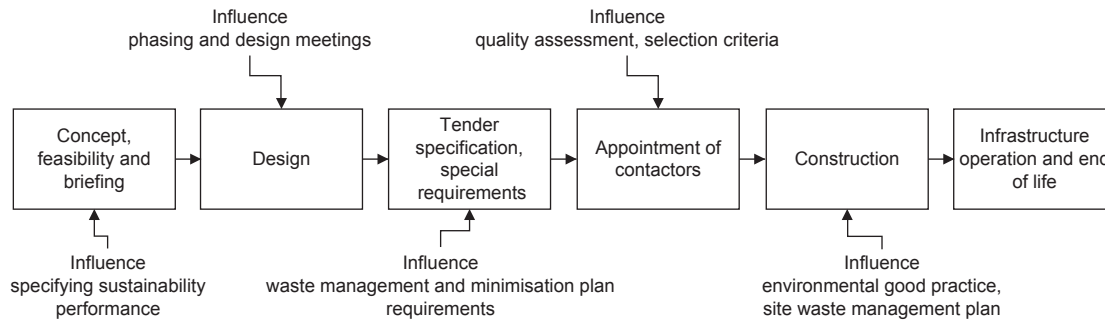


Figure 3. Points of influence through a project lifecycle

towards or away from sustainable development according to these objectives.

- (b) Tractability. Sufficient reliable numerical or qualitative data should be available to enable estimation of spatial and temporal trends.
- (c) Transparency. The indicators should be chosen in a transparent way so as to help stakeholders identify why indicators are being considered.
- (d) Practicability. The indicators must be practical in terms of time and resources available for any analysis and assessment.

The benchmark indicators were categorised into two groups based on the geographical scope of the indicator, either waterfront-specific or city/region wide; the former are focused on the development area, whereas the latter are based on the impact of the waterfront development at a city/region scale. An example of the latter type of indicator is retention of skills base, where an attribution of any change due to the central waterfront will be required. One of three forms of baseline data exists for each indicator

- (a) an initial baseline value for 2007 (e.g. population 142 170)
- (b) a value of 0 as a datum for 2007 (e.g. number of jobs created since 2007)
- (c) N/A (not available) if the indicator is not measurable at this time (e.g. per capita water consumption of new buildings as the area has not yet been developed).

The indicators will have different responsiveness to changes in the development. For some indicators, there will be a change in the indicator only at infrastructure stage or plot development stage, whereas some indicators will change at some or all of the development stages. For example, an indicator such as air quality will be influenced at each stage of the development but retention of skills base, which monitors graduate retention rate, will only be influenced at the plot development stage. A subset of

six indicators – two social, two economic and two environmental – were selected for modelling and visualisation in the tool.

3. Analytic network process methodology

The analytic network process (ANP) methodology uses interactive network structures to give a holistic representation of an overall problem (Saaty, 2006). The components in a network may be regarded as elements that interact and influence each other with 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 ANP analysis, a decision-maker must identify the network through analysis of the problem to be solved; clusters and elements, and the relationships and interactions between them, must be identified (Bottero *et al.*, 2007) (an example network for a sustainable development scenario is shown in Figure 4). With the network to be analysed thus constructed, the decision-maker must then create a super matrix that describes the interactions defined in the network (Gencer and Gurpinar, 2007). This is achieved by making judgements about the relative influence of each indicator of the model over each other indicator, using pair-wise comparison from the fundamental scale (Table 1) (Saaty, 1990). To illustrate the process, pair-wise comparisons of the top-level indicator network are shown in Figure 5, which illustrates that the stakeholder in this example rates economic factors 25 times more important than environmental factors for the social indicator.

Once a comparison matrix has been created, the elements must be prioritised; this is achieved by calculating the eigenvectors (normalised priority weights) of each attribute (Schneiderjans, 2004). These eigenvectors are then combined in the super matrix where every interaction is described in terms of every element it interacts with (Saaty, 1999). The super matrix is known as the

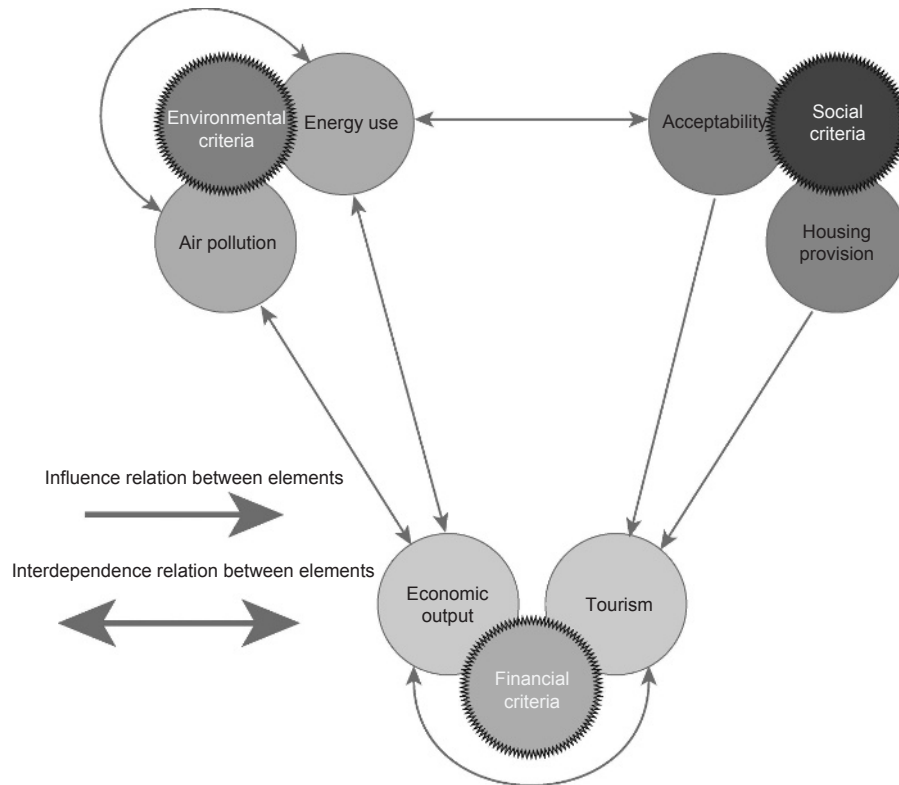


Figure 4. Example sustainable development ANP network model

initial or unweighted super matrix as it does not yet express the weightings of the overall clusters (Saaty, 1999; 2006). A pair-wise comparison matrix must be created to represent the relationship between the clusters, which in this case are environmental, economic and social. Once this has been completed the calculated eigenvector is applied to the unweighted super matrix and this results in a final weighted super matrix (Figure 6). The eigenvector calculated from the weighted matrix will give the decision-maker a prioritised list of sustainability indicators. This is a measure of indicator dominance for sustainability, to be used for augmentation with the sub-system indicator models and displayed using the visualisation.

Like all multi-criteria decision analysis techniques, the ANP methodology could become subjective if the pair-wise comparisons are not based on factual information. However, unlike many other multi-criteria analysis techniques, ANP is not a 'black box' and allows the weighting procedure to be completely transparent. Many fully worked examples of the ANP methodology applied to decision-making practices are available in Saaty (2006).

4. Sub-system models

Sub-system models define how the indicators change over time. The indicators currently used by the prototype tool are housing

provision, acceptability, economic output, tourism, energy use and air emissions. As an example, consider the energy use indicator. The current energy use model is an implementation of the standard assessment procedure (SAP), which is the government's own standard system for assessing the energy efficiency of buildings (Defra, 2008). The SAP model allows the stakeholder to change a wide variety of variables, including glazing type, insulation type, building materials and low-energy lighting. The SAP model then determines the effect of these variables on the energy use of the building. The maximum and minimum results for a sub-system are then obtained across all the scenarios being studied.

These are used to perform linear maximum–minimum normalisation on the results of each sub-system, to give a value between 0 and 100. To determine the sustainability of a specific building in an urban development at a given time, each of the normalised indicator values obtained from the sub-system models at that time point is multiplied by the weights/priorities provided by the ANP models. This gives a quantitative measure of sustainability for each building. It is important to note that the tool does not provide an absolute measure of sustainability but it does provide a mechanism to compare how alternative choices (e.g. different proportions of residential to commercial properties) change the

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 or demonstrated 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 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>i</i> has one of the above non-zero numbers assigned to it when compared with activity <i>j</i> , then <i>j</i> has the reciprocal value when compared with <i>i</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 <i>n</i> numerical values to span the matrix
1.1–1.9	For tied activities	Used when elements are close and nearly indistinguishable; moderate is 1.3 and extreme is 1.9

Table 1. The fundamental scale (Saaty, 1990)

relative sustainability. Figure 7 summarises the steps involved in the sustainability assessment.

5. Visualisation techniques

5.1 Blending

Each element (e.g. building, road) in the development will now have a sustainability value based on the range of selected indicators. These are then mapped onto a colour scale using a colour map. The tool is flexible and allows the user to select from numerous colour maps best known for their discriminating abilities (Levkowitz and Herman, 1992). In the colour scale

used; elements that are blue and red will have high and low sustainability values respectively. Blending is simply the combination of all indicators, resulting in a single sustainability value. The colour map can then be used to indicate sustainability. As an example, Figure 8 shows that each floor in a building can have a different level of sustainability.

5.2 Weaving

Rather than combining all the indicators into a single value, it may be possible to preserve some of the underlying information so that indicators or clusters that are very unsustainable or

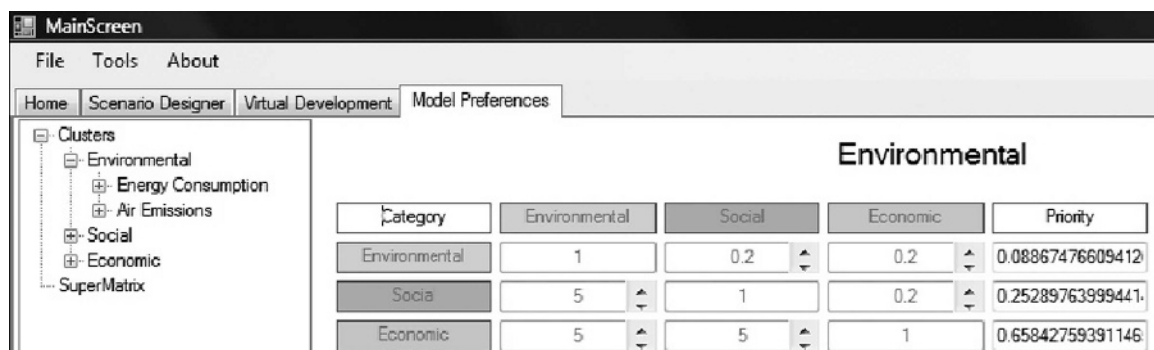


Figure 5. S-City VT dialogue for setting ANP parameters (i.e. defining the network)

Category	Air Pollution	Public Transport	Social Inclusion	Neighbourhood Sat	Employment	Population	Priority
Air Pollution	0.2	0.2	0.2	0.1656667	0.1656667	0.1428572	0.09978837
Public Transport	0.8	0.8	0.8	0.8333333	0.8333333	0.8571428	0.273545
Social Inclusion	0.2	0.125	0.2	0.1428572	0.2	0.1428572	0.09615081
Neighbourhood Sat	0.8	0.875	0.8	0.8571428	0.8	0.8571428	0.2771625
Employment	0.1428572	0.2	0.1428572	0.125	0.2	0.25	0.09892858
Population	0.8571428	0.8	0.8571428	0.875	0.8	0.75	0.2744047

Figure 6. The resulting super matrix giving priorities/weightings for each indicator value

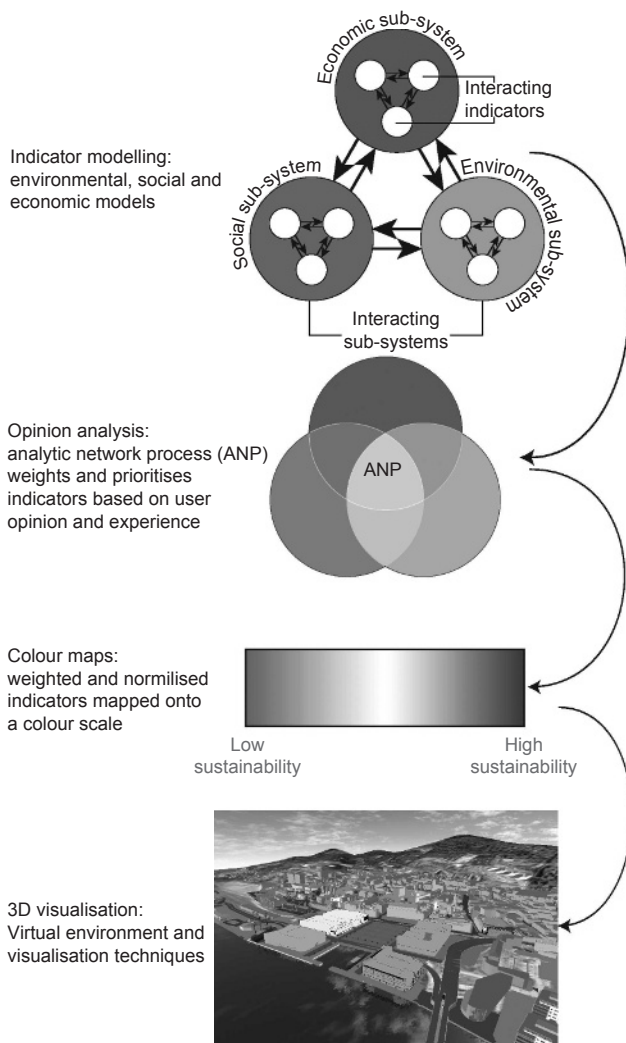


Figure 7. Steps involved in computational and visualisation tool

very sustainable can be identified. A weaving technique (Hagh-Shenas *et al.*, 2007) that uses a different colour map per indicator could be used to preserve this information (see Figure 9). The tool would allow zooming into one building so that each indicator value could be determined. This will become more complex as the number of indicators being shown increases, but the user will be able to turn off indicators that are not of interest to prevent this over complexity.

5.3 3D visualisation of the development

Finally the visualisation technique is applied to the 3D development (Figure 10).

6. Tool application and testing

Testing of the tool will be undertaken using the Dundee central waterfront development project as a case study. The parallel research work on the implementation of a sustainability enhancement framework for the central waterfront development informed the choice of sustainability indicators and identified the key stakeholders in the decision-making processes.

The final decision in any decision-making process is rarely made by one person; this is especially true in the urban planning domain. For this reason, testing will use focus groups to simulate the types of consultation and engagement meetings in which it is envisaged the tool will ultimately be used. This group methodology will allow a much better insight into the group decision-making process than a questionnaire or solo interview, and will also provide observational data that would be inaccessible without the interactions found in a group (Morgan, 1997). The focus groups used will ideally comprise six to ten members of a single stakeholder group; this will allow the greatest range of opinions without reducing the depth and substance of discussions (Gilbert, 2001).

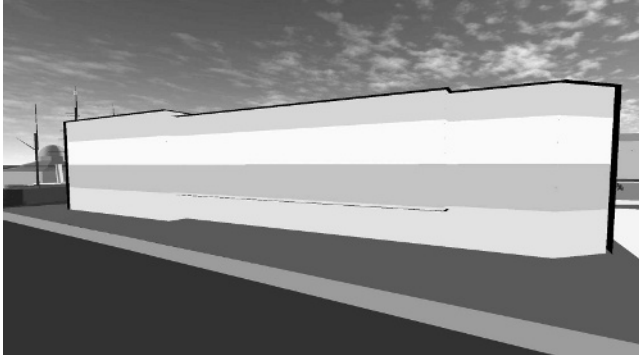


Figure 8. Sustainability visualisation using colour mapping

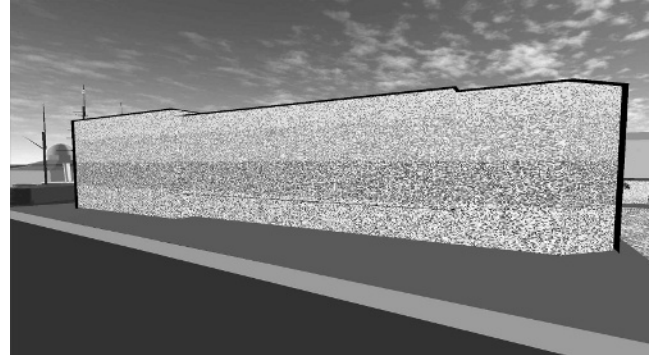


Figure 9. Sustainability visualisation using colour mapping

As usability trials are most effective when participants represent real users performing real tasks (Dumas and Redish, 1999), the stakeholder groups will be presented with two scenarios, running simultaneously using a split-screen display, as shown in Figure 11. The two chosen scenarios will have different levels of sustainability known only to the researchers. The discussions and final conclusion (i.e. which scenario was deemed to be relatively more sustainable) of the group is then recorded and analysed to assess how the group's ability to make judgements on the relative sustainability of the separate scenarios is guided by the tool. The testing will not only provide an insight into which of the different visualisation techniques or combination of techniques is preferred by each stakeholder group, but also which techniques are most efficient at conveying sustainability information.

This testing methodology was piloted using two 'stakeholder' groups composed of University of Abertay Dundee students at various stages of their degree courses. Each group was shown two scenarios that displayed a high degree of difference (100%) in their relative sustainability. The group was asked to determine, using the blend technique, which of the scenarios was the most sustainable. Both groups were able correctly to identify the most sustainable scenario and, on analysis of the recordings of each meeting, it was also shown that each group's decision was unanimous.

The groups were then shown two more scenarios, with an 80% difference in their relative sustainability. Using the weave technique, the group was asked to determine which scenario was the most sustainable *and* identify which indicator was having the greatest negative impact. Again, both groups were able to identify which scenario was the most sustainable and clearly to identify which colour stood out the most (and therefore which indicator was most significantly lowering the sustainability of the scenario).

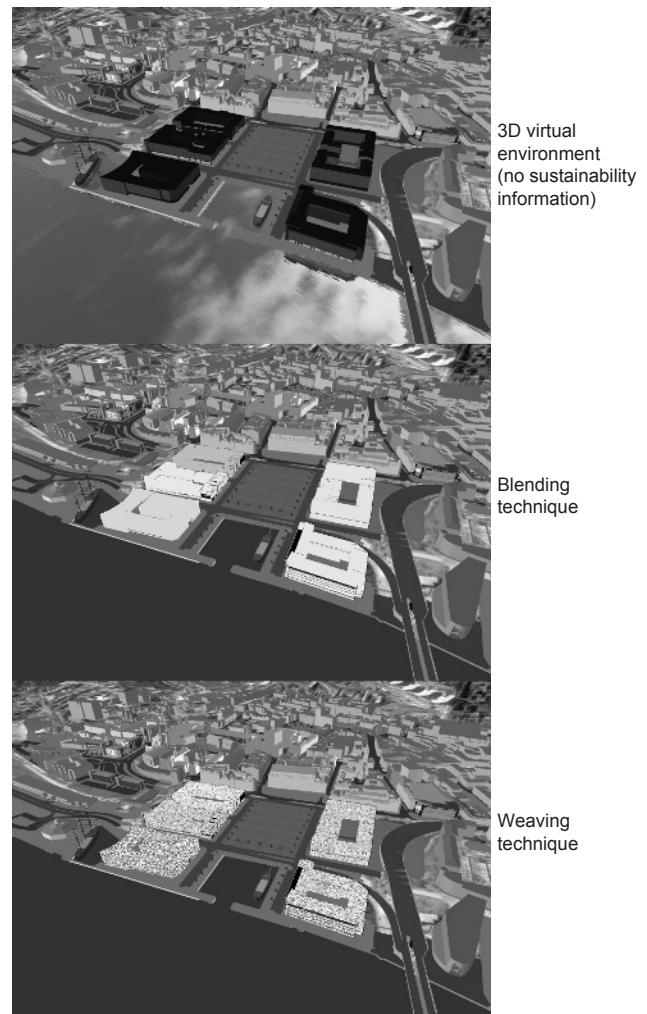


Figure 10. 3D visualisation of development with and without sustainability information

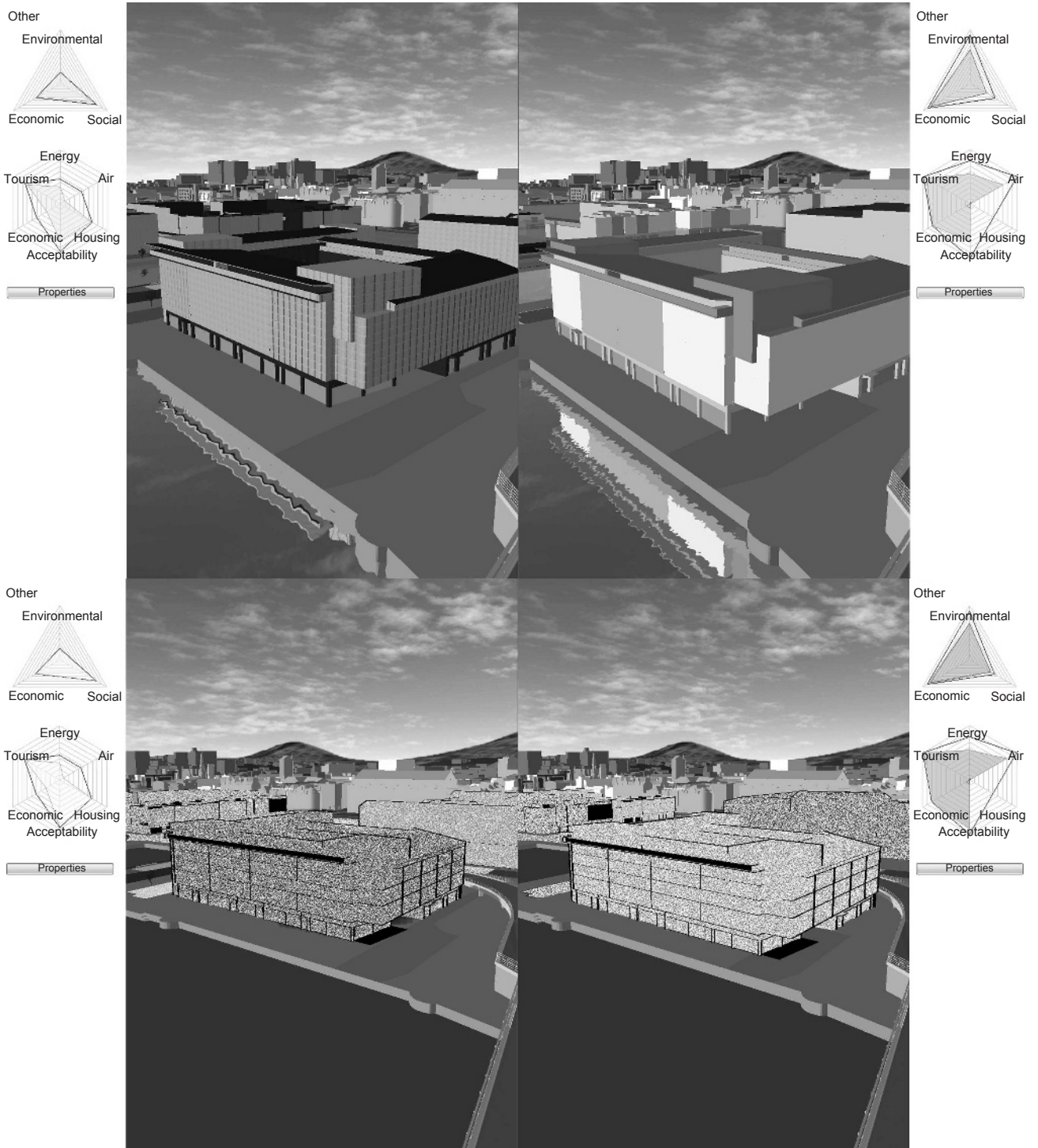


Figure 11. Comparison techniques used for testing

The third test was designed to determine – for both blending and weaving techniques – the limit at which stakeholders can no longer determine a difference in sustainability between two scenarios. For each technique, the groups were shown a number of scenarios with increasing differences in their sustainability at 10% intervals from 0 to 100%. For both techniques, the participants, both as a group and individually, were able correctly to identify the most sustainable scenario down to the 10% difference. They were also able to identify which indicators were having the biggest impact on lowering sustainability using the weave technique. Although the participants said that the weave technique was harder to interpret initially due to its complex nature, they all agreed that as their exposure to the weave technique increased interpretation became easier.

An interesting observation was that one member of one group had some difficulty in determining when there was no difference between the scenarios using the blend technique; however, the majority of the group did correctly determine that the scenarios were the same. As the pilot test only tested 10% intervals, it was not possible to determine if participants could identify differences in the range between 0 and 10%. Further testing will therefore be performed on this range.

The pilot tests show that the majority of participants had no problems identifying the differences in relative sustainability of the scenarios they were shown. However, more testing will need to be performed using different stakeholder groups to ascertain the tool's effectiveness more thoroughly.

7. Conclusions

Sustainability visualisation techniques provide an effective means of demonstrating relative sustainability changes to a wide range of stakeholders in the urban design and planning process. By projecting the results of a simulation model onto a virtual representation of an actual development, the tool allows the user immediately to envisage the consequences of any decisions taken and the differences in specific scenarios over time. The use of visualisation techniques in this way begins to remove sustainability assessment's reliance on existing expert systems that are largely inaccessible to many stakeholder groups, especially the general public. Furthermore, usability testing has revealed which visualisation techniques are effective in terms of conveying sustainability information to a specific stakeholder group. Since the tool is generic it can be easily applied to different complex urban data; for example, the indicators could be changed to model demographic changes. The indicators can also be extended to include below-ground geotechnical indicators that would affect urban sustainability.

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