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Integrated modelling for Sustainability Appraisal of urban river corridors: Going beyond compartmentalised thinking

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ABSTRACT

Sustainability Appraisal (SA) is a complex task that involves integration of social, environmental and economic considerations and often requires trade-offs between multiple stakeholders that may not easily be brought to consensus. Classical SA, often compartmentalised in the rigid boundary of disciplines, can facilitate discussion, but can only partially inform decision makers as many important aspects of sustainability remain abstract and not interlinked. A fully integrated model can overcome compartmentality in the assessment process and provides opportunity for a better integrative exploratory planning process.

The objective of this paper is to explore the benefit of an integrated modelling approach to SA and how a structured integrated model can be used to provide a coherent, consistent and deliberative platform to assess policy or planning proposals. The paper discusses a participative and integrative modelling approach to urban river corridor development, incorporating the principal of sustainability. The paper uses a case study site in Sheffield, UK, with three alternative development scenarios, incorporating a number of possible riverside design features. An integrated SA model is used to develop better design by optimising different design elements and delivering a more sustainable (re)-development plan. We conclude that participatory integrated modelling has strong potential for supporting the SA processes. A high degree of integration provides the opportunity for more inclusive and informed decision-making regarding issues of urban development. It also provides the opportunity to reflect on their long-term dynamics, and to gain insights on the interrelationships underlying persistent sustainability problems. Thus the ability to address economic, social and environmental interdependencies within policies, plans, and legislations is enhanced.

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1. Introduction

Rivers have played a key role in the development of our towns and cities. However, urban rivers and their corridors suffer from a legacy of industrial and domestic pollution, intensive channel modifications, industrial dereliction and a lack of public access (Paul and Meyer, 2001; Walsh et al., 2005). Riverside locations are now prime sites for redevelopment and a re-evaluation of the role and value of urban rivers to society is taking place (Findlay and Taylor, 2006). Attractive waterfronts have high value as places to live and work (e.g. Luttik, 2000). Urban river corridors are being appreciated for the recreation, aesthetic and cultural heritage values that they provide and for the biodiversity that they are able to support (Findlay and Taylor, 2006). However, they can also suffer major damage due to flooding, and the needs of flood defence may be at odds with some of the other services provided by urban river corridors. The challenge of managing such areas is to balance the needs of potentially conflicting uses to best meet the needs of society in the 21st century. One way to achieve this balance is through the use of an integrated Sustainability Appraisal of redevelopment proposals.

Over the past half-century, continuous effort has been made to define sustainability as a broad concept that pushes beyond the economic agenda to be a more complete treatment of human and ecosystem well-being (Hodge, 1997). In early 2005, the UK launched a new strategy for sustainable development (Force, 2005). Sustainability Appraisal (SA) was later made mandatory under UK legislation (DCLG, 2008) and now the National Planning Policy Framework (2012) has made sustainable development the central plank of the English planning system. SA allows urban development plans to be assessed based on a range of criteria that address all the impact issues. At the same time, the concept of ecosystem services has gained considerable attention from policy makers and practitioners. The ecosystem services concept is strongly related to sustainability appraisal in that both ideas are anthropocentric and based around human needs. Ecosystem services are the benefits that people derive from natural capital (MEA, 2005), whereas SA goes beyond the natural environment to also consider the effects of built, human and social capital (Wu, 2013). Human dominated ecosystems are linked social-ecological systems, where human and environmental components interact (Alberti et al., 2003). Urban river corridors provide a particularly good example, where human well-being is influenced by the complex interactions of the built and natural environments. Redevelopment of such areas provides an opportunity to enhance well-being through careful consideration of both realms, using SA as a key assessment tool.

The primary goal of SA is to inform and improve strategic decision making (Sheate et al., 2008). Much of the literature in SA has argued that classical assessments are compartmentalised and fail to involve vision and understanding of the interrelations and interdependencies of environmental, economic and social considerations (Salter et al., 2010). SA aims to achieve a simultaneous consideration of social, economic and environmental issues and to produce a "win–win" outcome, with minimal trade-offs. How environmental, social and economic information is analysed, integrated and presented to decision-makers is the most critical concern of SA. The assessment relies on the application of a variety of methods of enquiry and argument to produce policy-relevant information that is then utilised to evaluate the consequences of human actions against the normative goal of sustainable development (Stagl, 2007).

Over the last few decades, a plethora of approaches and methods for SA have been proposed. The Large Urban Distressed Areas project identified 27 SA techniques that have been recently cited and are distinguished by different theoretical underpinnings and practical applications (LUDA, 2006). SA methods have also been subject to continuous debate regarding, for example, the definition of indicators capable of incorporating the complexity of cause–effect relationships inherent in urban policies, and the usability, transparency and transferability of models (Campo, 2009).

Sustainability-based planning is a complex task that involves integration of social, environmental and economic considerations into a formal plan that often requires trade-offs between multiple stakeholders that may not easily be brought to consensus. Such interactions can be conflicting or synergistic with respect to the different management objectives. Integrated assessment provides an opportunity to make planning more efficient with more synergy and less conflict (Holzkämper et al., 2012) and to identify new and innovative solutions that can make urban development more sustainable. The complexity surrounding SA calls for an integrated approach to science, policy and management that transcends existing disciplinary and cognitive boundaries. Integrated modelling is based on combining, interpreting and communicating knowledge from diverse scientific disciplines to policy in such a way that an entire cause–effect chain of a problem can be evaluated from a synoptic perspective.

This paper examines the problem of master planning for the redevelopment of urban river corridors where water related issues are just some of the multiple objectives that have to be achieved. We test the hypothesis that a tool for integrated SA supports the design process by identifying key variables that contribute to multiple objectives and by quantifying uncertainty. We use a case study site in Sheffield, UK to develop and illustrate our model by creating a structured integrated model to assess alternative redevelopment proposals.

2. Integrated model development for Sustainability Appraisal

2.1. *Sheffield case study site*

Our integrated sustainability model was tested for an urban redevelopment site in Sheffield, UK. The 113,000 m^2 site lies on the northern edge of the city centre, adjacent to the River Don (Fig. 1). It was once the most important gateway to the city, but has stagnated in recent years and is now subject to a major regeneration plan led by Sheffield City Council (Council, 2007). Wild et al. (2008) present background information on the key

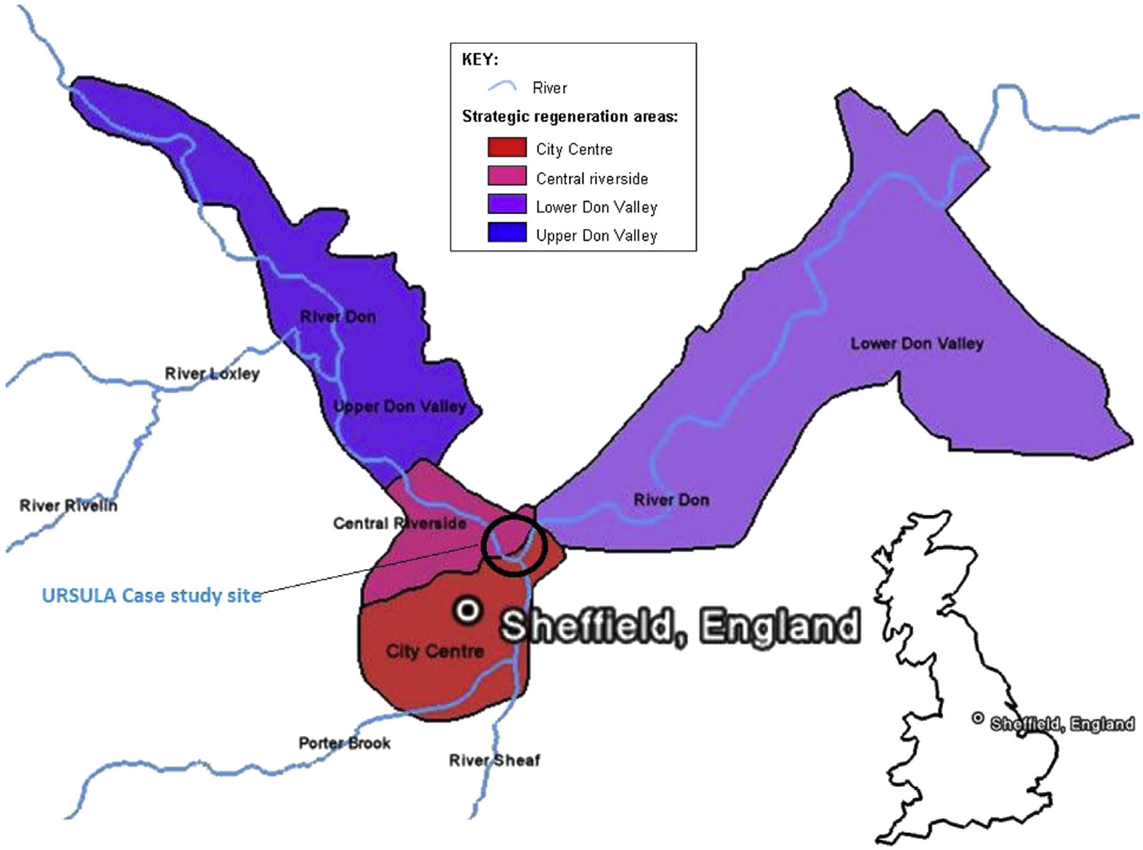

Fig. 1 – River corridors and strategic regeneration areas of Sheffield. Large circle showing study site. Map has been adapted from source map from University of Sheffield. Strategic Regeneration Areas courtesy of Sheffield City Council.

social, economic and environmental trends pertaining to Sheffield's urban river corridors, drawing on a wide range of references and information sources. Three alternative scenarios were developed and visualised for this project and have been named Council, Street and Flood scenarios by us. All shared a series of common goals, as set out in the regeneration plan for the area (Council, 2007), including achieving radical improvements in the quality of the public realm, reconnecting the area with the River Don, encouraging walking and cycling, addressing flood risk issues, promoting sustainability, and respecting historic heritage. The first scenario, called the Sheffield City Council & Environment Agency scenario (henceforth Council), comprised the re-development proposals put forward by Sheffield City Council in their Wicker Riverside Action Plan (Sheffield City Council, 2007) along with flood channel clearance works proposed by the UK Environment Agency to reduce flood risk in the area. The other two scenarios are hypothetical research scenarios designed by the URSULA project team called Street and Flood Channel respectively. These latter scenarios were designed to be highly contrasting, drawing out different possible elements of riverside redevelopment. A summary layout of the current situation and the three redevelopment scenarios are shown in Fig. A-1 and main features are provided in Table A-1. A detailed description of these scenarios has been provided in Pattacini et al. (2010).

2.2. *Integrated model for Sheffield urban river corridor (URSIM)*

Various modelling techniques can be used to develop integrated models (Kumar et al., 2008). In recent years, Bayesian Networks (BN) have been successfully used to develop such integrated assessment tools, by combining expert opinions, empirical evidence and other information such as surveys, and model simulations (Holzkämper et al., 2012). The BN approach is based on a directional graph representing cause–effect relationships in the system. Comprehensive guidelines on the application of BNs in support of participatory planning have been provided by a number of authors (Bromley et al., 2005; Barton et al., 2012; Borsuk et al., 2012).

URSIM is implemented as a Bayesian Network (BN). In a BN, variables are linked together according to their dependencies (Jensen and Nielsen, 2007). Associated with each variable is a conditional probability table (CPT), which specifies how this variable is affected by its influencing variables. The CPTs can be derived from data, external model results or expert knowledge (Varis, 1998), which provides the opportunity to integrate and combine information from different sources in one model. The BN can be built to any level of detail and thus allows us to simplify complex relationships. Further advantages of the BN approach are that rapid scenario analyses can be performed and uncertainties in model predictions can be explicitly considered. The explicit consideration of uncertainties is an important asset to decision making, particularly in the complex systems of urban development.

URSIM model was developed in the following major steps:

a) *Identification of criteria to represent relevant aspects of the sustainability objectives*:

A full range of environmental, social and economic criteria were identified and refined for use in a SA (Table 1). These were adapted from a list of sustainability objectives produced by Sheffield City (Council, 2005) and reflect local and national priorities and guidelines. They include ecological concerns and river issues but are not driven by them, because the river is only part of the urban river corridor and the criteria must reflect the wider set of issues of concern to the city.

b) *Mind Mapping*: *Development of conceptual cause–effect networks around each sustainability criterion*:

A wide range of experts and stakeholders were invited to participate in the assessment process. In total, 32 experts scored the current situation and the three redevelopment scenarios for selected sustainability criteria, based on their areas of expertise. This was a classical approach to SA based on subjective scoring. Scenarios were scored on a 9-point scale, from 1 (substantial detriment) to 9 (substantial improvement) compared to the current situation, with 5 indicating no net change. At the end of the SA, the experts took part in an exercise to determine how these decisions were reached and to identify which elements were important in determining each sustainability objective. They were quizzed on the scoring criteria and logic they used. This process was used to derive a conceptual network for each sustainability criteria depicting the cause and effect relationships. We call this exercise "mind mapping" and the conceptual network a mind map.

c) *Integration and simplification of conceptual sub-networks*:

Several experts contributed to each sustainability criteria and each expert produced their own version of a mind map. To get the final network for each sustainability criteria, the mind maps were simplified and integrated. Cause–effect links and variables with minor relevance were excluded, as well as links and variables that could not be influenced through any of the management actions under consideration. Links and variables that could not be specified due to insufficient data or knowledge were also excluded. A fundamental step here was to reach an agreement on the structure of a simplified network that could finally be implemented as a BN. Experts involved in the process were consulted to get their feedback and build consensus on the final mind map. Fig. 2 shows a simplified process of integrated conceptual model development for "Natural Landscape" with the participation of three subject knowledge experts. The actual process for each criterion involved 5–10 experts and more complicated networks.

d) *Classification and specification of model variables*:

After finalisation of the conceptual sub-models for each criterion, system or design variables were defined based on empirical knowledge or the experts' advice. Sometimes definitions of common variables need consensus across different disciplines. Once definitions were agreed, variable values were split into three broad categories of High, Medium and Low (or three other terms appropriate for the individual variables). These categories were defined with context specific knowledge.

e) *Integrated Model*: *Merging of sub-networks*

Once the different sub-models were specified, they were merged into the overall integrated model for the Sheffield

Table 1 – List of 15 sustainability criteria assessed by experts and used in URSIM model development.

	Criteria	Short description
1	Business Support	Supporting business, growth and investment
2	Property Value	Uplifting property values
3	Investment Return	Achieving return on investment
4	Decent Housing	Decent housing available to everyone
5	Health & Wellbeing	Conditions and services which engender good health and wellbeing and provide leisure and recreation opportunities for all
6	Safety & Security	Safety and security for people and property
7	Sustainable Transport	Land use patterns that minimise the need to travel or which promote the use of sustainable forms of transport
8	Land Use efficiency	Efficient use of land which makes good use of previously developed sites and buildings
9	Quality Built Environment	A quality built environment
10	Historic Environment & Cultural Heritage	Historic environment and cultural heritage protected and enhanced
11	Natural Landscape	Quality natural landscapes maintained and enhanced/created
12	Biodiversity	Wildlife sites and biodiversity conserved and enhanced
13	Water Resource	Water resources protected and enhanced
14	Flood Risk	Minimal risk to human life and property from flooding
15	Energy & Climate Change	Prudent and efficient use of energy and resilience to climate change

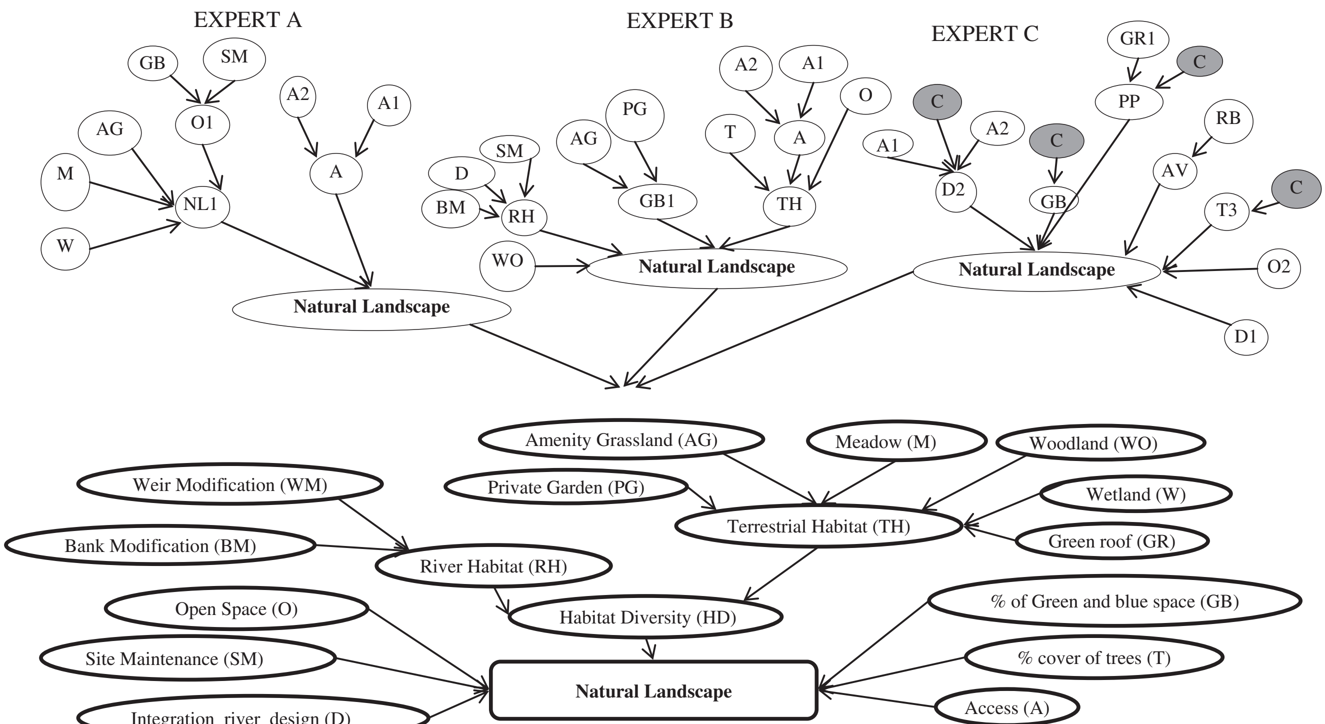

Fig. 2 – Conceptual model development for criteria "Natural Landscape". Bubbles marked 'C' are not considered in final network. Bubbles marked 'Xn' are variants of variable 'X'.

urban river corridor. Integration of sub-models was achieved by linking common variables across different sub-models. Fig. 3 shows the Network implementation of the integrated model developed as a Bayesian Network.

f) *Knowledge elicitation*

Knowledge elicitation is the process of making implicit knowledge explicit – helping experts recall, test and refine their rules-of-thumb, heuristics and past experiences. Before starting the probability elicitation process, experts have to agree with the model structure, the definitions of the variables and the variable discretisation. For this project, knowledge was elicited from the same experts involved in the first phase of the SA and mind mapping exercise. We had 32 experts in total covering different criteria and a minimum of five experts were interviewed for each criterion. We applied a modified version of the relative weight and compatible probability method proposed by (Das, 2004) to reduce the number of questions to be asked and thus the elicitation effort. Thereby we consider system nonlinearity that is characteristic for natural systems by eliciting special cases when influencing variables are critical and produce threshold responses. The elicited probabilities were checked for inconsistency and median values of combined probabilities were used to train the Bayesian Network model.

g) *Model testing and evaluation*

URSIM was tested by evaluating the different design scenarios developed for the Sheffield test case (Fig. A-1 & Table A-1). The model input variables were scored by project experts independently for each scenario and used as input for the model to evaluate each scenario. The final scores were compared with the scores previously obtained by the traditional SA approach using experts' assessment (Step b above).

h) *Sensitivity and degree of integration*

URSIM can be used to optimise the planning process by improving design scenarios for a given set of planning objectives. In the Sheffield case study we used URSIM to select important design variables and then improved the design of the scenarios in respect of those variables. Normally, sensitivity analysis is used to decide the importance of variables in the model. However in URSIM, the sensitivity scores of variables may have subjective weight anomalies. In such a network model, the influence of system variables are felt across all criteria, but structural bias as a result of weak links can reduce this influence. We applied the Graph theory measure of centrality – 'Degree of Integration' – which gives the structural importance of variables in a graphical network and combined it with sensitivity scores, to select the key variables.

Sensitivity to findings was calculated in order to guarantee that the BN model correctly represented this environmental problem. Sensitivity to findings determines whether evidence of one variable may influence belief in a query variable (Pollino et al., 2007). We analysed the structural sensitivity of system variables by understanding inter-connectivity and sensitivity towards different criteria. All measures of centrality aim at

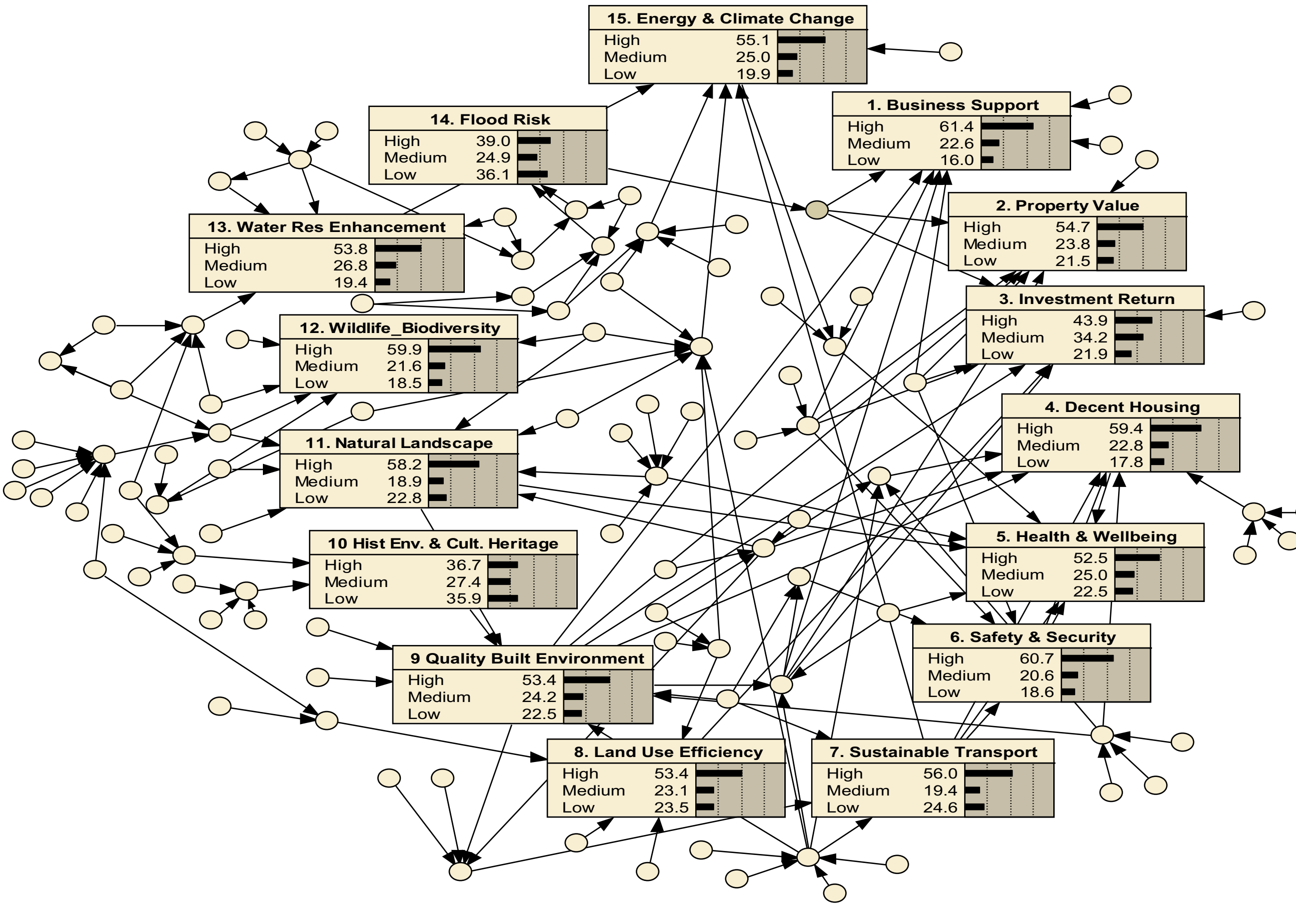

Fig. 3 – Bayesian Network implementation of integrated model for URSIM. Numbered boxes are showing criteria and bubbles are system variables.

quantifying the prominence of an individual node embedded in a network, but they differ on the method used to achieve that. Given the subjectivity of the term "importance", it is not surprising that there are various measures of centrality in Graph Theory. For measuring Degree of Integration (DI), we have used the inverse of geodesic distance between target vertices, counting only incoming links. The maximum DI score is 1 for a direct link (network link depth of 1) and decreases as the depth of the link increases (for depth of 2 DI = 0.5, for depth of 3 DI = 0.33 and so on). We have limited our analysis of DI of input nodes to the sustainability criteria. Table 2 is a summary of the degree of integration of important variables.

3. Results & discussion

3.1. General results

All scenarios were analysed using both classical expert assessment and the integrated model URSIM. The classical assessment used the current situation as a baseline, with alternative scenarios analysed for their relative improvement or deterioration from that state. URSIM used absolute scores for all four scenarios based on the state of 70 input (design) variables which define the characteristics of the different scenarios. However both approaches have used the same scale for the final categorisation of criteria. Summaries of sustainability scores are presented in Fig. 4a for the experts' assessment and in Fig. 4b for the model assessment.

The Council and Street scenarios achieved a broadly similar pattern of results across the set of sustainability criteria, although the Street scenario scored consistently higher for most. The Council scenario scored particularly poorly for natural landscapes and biodiversity, where it was judged by experts to be moderately detrimental compared to the current situation. Both scenarios scored highly for the economic indicators (business, property values, and return on investment). In contrast, the Flood scenario presents a very different pattern of results according to the expert assessment, reflecting its radical departure from the current situation and the other scenarios. It scored less well for all three economic indicators, particularly for the indicator 'supporting business, growth and investment'. It was considered to be detrimental to the historic environment and cultural heritage, as it removes some historic features and radically alters the character of the area. On the other hand, this scenario scored

Table 2 – Summary of sensitivity analysis and degree of integration of selected variables.

Variable	Sensitivity score	Degree of integration	Criteria
Flood Defence	7.91	0.33	1. Business Support
	6.6	0.33	2. Property Value
	8.26	0.33	3. Investment Return
	77.82	0.5	14. Flood Risk
Green and blue space	0.7	0.5	5. Health & wellbeing
	39.79	1	11. Natural Landscape
	2.45	0.5	15. Energy & Climate Change
Tree cover	8.34	1	11. Natural Landscape
	21.88	1	12. Biodiversity
Variety of recreation	3.13	0.5	1. Business Support
	6.61	0.5	2. Property Value
	7.83	0.5	3. Investment Return
	67.22	1	5. Health & wellbeing
Permeability	1.27	0.5	2. Property Value
	1.18	0.5	3. Investment Return
	9.54	0.5	4. Decent Housing
	8.59	0.5	5. Health & wellbeing
	32.95	0.5	6. Safety & Security
	92.75	1	7. Sustainable Transport
	37.08	1	9. Quality Built Env.
	5.69	0.5	15. Energy & Climate Change
Derelict Land	14.54	1	1. Business Support
	29.69	1	2. Property Value
	18.93	1	3. Investment Return
	35.32	1	6. Safety & Security
Site Maintenance	9.08	0.5	1. Business Support
	6.49	0.5	2. Property Value
	15.51	0.5	3. Investment Return
	17.39	0.5	6. Safety & Security
	31.5	1	11. Natural Landscape
Permeable area	25.23	1	13. Water Resource
	0.5	0.33	14. Flood Risk
	0.71	0.5	15. Energy & Climate Change

very highly for most environmental indicators, especially 'natural landscapes' and 'wildlife sites and biodiversity', where it achieved much higher scores than the other scenarios. It was the highest scoring scenario for 7 of the 15 indicators in the expert assessment.

A comparative analysis of experts' assessment and model scores has been provided in Fig. 5a. Sustainability criteria scores for the three re-development scenarios were broadly similar. The Council scenario showed the best agreement between both methods, with a correlation of 0.89, followed by Street ($r = 0.62$) and Flood scenario ($r = 0.52$). Though the score has been fixed to 5 in the experts' assessment of the current situation, the general consensus of experts was that the current state of the site is poor for all sustainability criteria. This has been reflected in the URSIM model results in which the current situation scored below average for most of the sustainability criteria. It is interesting to note that there is higher variability for the environmental criteria than economic and social ones, reflecting higher uncertainty in experts' responses.

Apart from the summarised scores for sustainability criteria, URSIM can be used for more detailed analysis. The distribution of scores over high, medium and low states reflects the uncertainty of prediction. For example Fig. 6a shows the predictions of Natural Landscape for all four scenarios. For the current state and the Council scenario, predictions average as Medium but have high uncertainty as Low and High states are equally likely. In contrast, predictions for Street and Flood scenarios are more certain, with a high probability of achieving a High state.

All 112 variables (70 input variables + 42 intermediate variables) were included in the sensitivity analysis of the integrated BN. However, we set a threshold to select the most significant variables; there sensitivity analyses are shown in Table 2. A detailed sensitivity analysis can be used to identify important design variables which influence the scores of particular criteria, and the example of Natural Landscape is shown in Fig. 6b.

Two scenarios, Council and Street, were tested for improvement using URSIM, with the results shown in Fig. 5b. Overall, the aim was to improve the sustainability score of these scenarios. Important design parameters were selected from the sensitivity analysis and altered to improve those scenarios. The new Council scenario showed significant improvement from the original council scenario. However the new Street scenario produced little improvement over the previous version; as it already had high scores there was little scope for large improvements in the sustainability criteria.

3.2. *Compartmentality analysis*

Classical SA is based on the qualitative judgement of subject matter experts. Each expert scores respective sustainability criteria based on their professional judgement. It may involve some cognitive mapping, analysis of available information, and limited multi-disciplinary analysis. However the capacity of human minds to perform broad integrated analysis is limited and this may limit the experts' capacity to perform complex integrated assessment on the scale presented in Fig. 3. The model structure for URSIM has been derived from multiple mental mapping of experts and it reflects their general knowledge from different disciplines. We expect that broader integration and general consensus of different experts through the integration required to create URSIM will have removed many of the disciplinary biases. The URSIM assessment should be less compartmentalised than the classical assessment.

Structural integration of URSIM has been tested by performing a Degree of Integration (DI) analysis between different sustainability criteria. The DI score was calculated for incoming links to the criteria listed in column 1 in Table 3. The higher the DI score, greater the integration between criteria. The sum of the DI scores for each row is called the Degree of Centrality and it reflects the multi-disciplinarily effect on criteria present in that row. A higher score reflects greater multi-disciplinarily effect on the target criterion and the influence it receives from other criteria in the model. The sum of the DI scores for each column is called the Degree of Diffusivity and reflects the effect of the target

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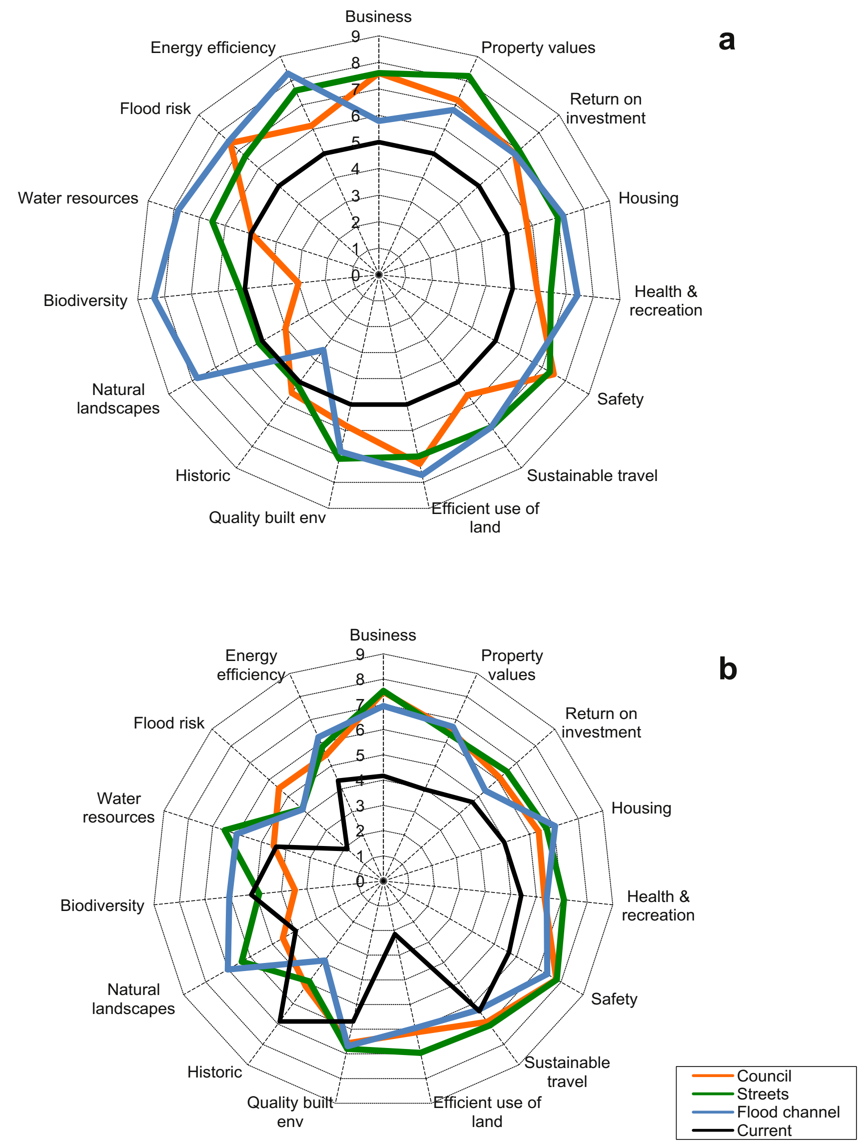

Fig. 4 – a) Results of the SA for three alternative re-development scenarios. b) Results of the SA using URSIM for three alternative re-development scenarios and current scenario. Scores range from 1 (substantial detriment) to 9 (substantial improvement), with a score of 5 (highlighted in bold) indicating that the scenario is neutral compared to the current situation.

criterion on other criteria. A higher degree of diffusivity score reflects a greater multi-disciplinarily role for that criterion.

In URSIM "Health and Wellbeing has the highest degree of centrality of 4.41 whereas "Natural landscape" has the highest degree of diffusivity of 4.16, as shown in Table 3. However the degree of diffusivity of Health and Wellbeing is just 1 while the Degree of Centrality of Natural Landscape is 0. These scores provide useful information regarding the nature of compartmentality in the model, the nature of the criteria themselves and their importance in urban design. For example, Health and Wellbeing is the most influenced by other criteria, but it has very limited influence on them. In contrast, Natural Landscape exerts a high influence on other criteria but is not influenced by them.

Most of the criteria in URSIM have either a high degree of centrality or a high degree of diffusivity. However, "Quality Built Environment" has an exceptionally high degree of centrality (2) and a high degree of diffusivity (3.99). Further, the economic criteria in general are influenced by other criteria but do not exert influence. Perhaps because we did not consider wider macro-economic drivers, those economic criteria that are relevant at a site level are very much dependent on the quality of the natural and built environments. "Decent Housing" and "Health and Wellbeing" are also very dependent on the quality of the natural and built spaces. On the other hand, none of the environmental criteria are influenced by the non-environmental criteria, but generally have strong influence on them. This may reflect the importance of the natural environment on economic and

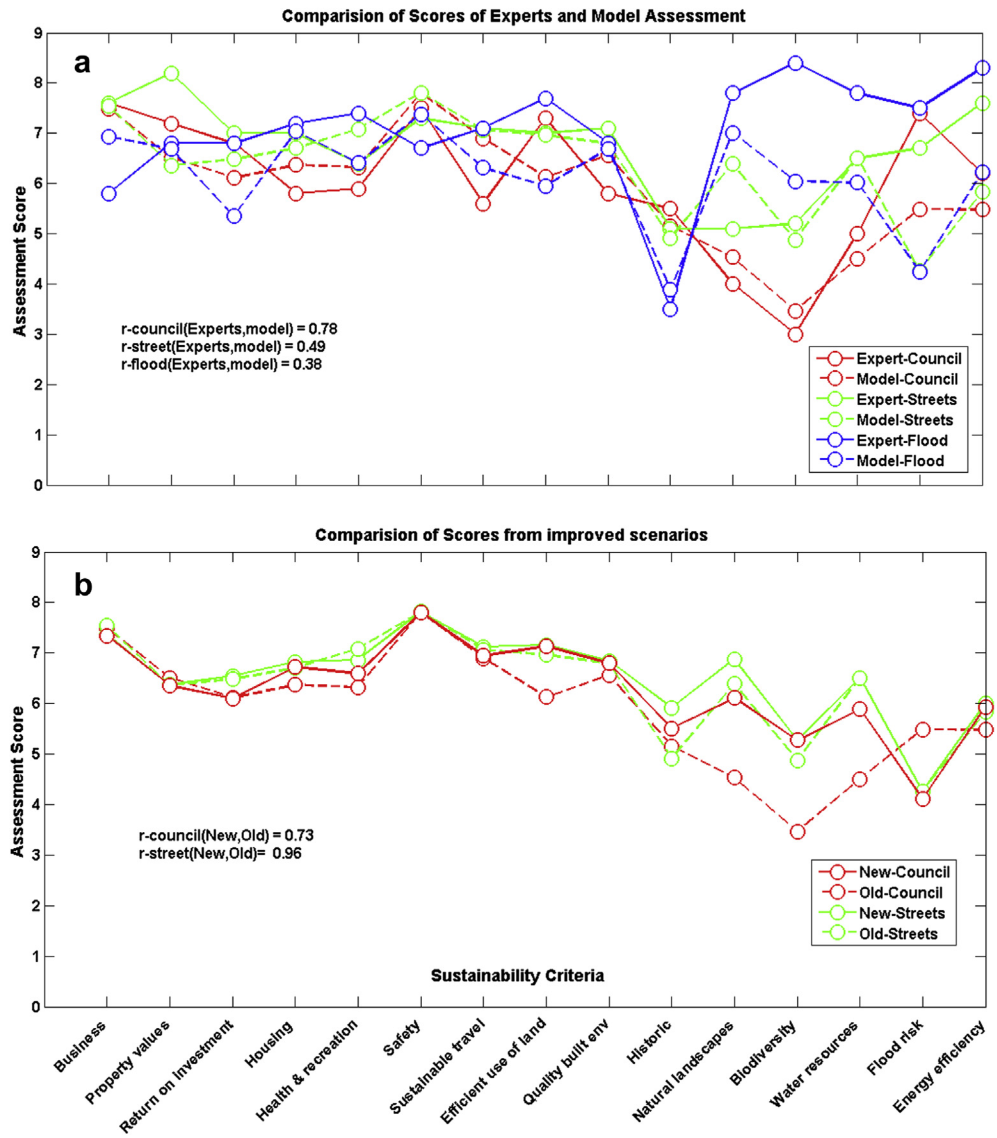

Fig. 5 – a) Comparison of experts' and model sustainability assessment for three alternative re-development scenarios. b) Performance of improved scenarios (results of the sustainability assessment using URSIM for two improved and two old scenarios). Scores range from 1 (substantial detriment) to 9 (substantial improvement).

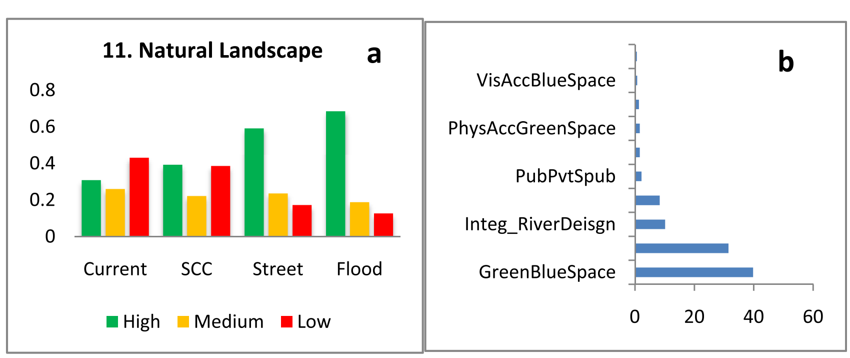

Fig. 6 – a) Categorised score for sustainability criteria Natural Landscape using Bayesian network model URSIM for four development scenarios. b) Sensitivity analysis for criteria Natural Landscape enlisting percentage scores for different input variables.

Table 3 – Summary of compartmentality analysis. The upper diagonal shows the Degree of Centrality between criteria (the influence of other criteria on that criterion). The lower diagonal shows the Degree of Diffusivity (the influence of that criterion on other criteria).

Criteria	BS	PV	IR	DH	HW	SS	St	LUE	QBE	HECH	NL	B	WR	FR	ECC	Centrality score
Business Support (BS)	_	0	0	0	0	0	0	0	1	0.5	0.5	0	0	1	0	3
Property Value (PV)	0	_	0	0	0	0	0	0	1	0.5	0.5	0	0	1	0	3
Investment Return (IR)	0	0	_	0	0	0	0	1	1	0.5	0.5	0	0	1	0	4
Decent Housing (DH)	0	0	0	_	1	1	1	0	0.33	0.25	0.25	0	0	0	0	3.83
Health & Wellbeing (HW)	0	0	0	0	_	1	1	0	0.33	0.25	1	0	0.33	0	0.5	4.41
Safety & Security (SS)	0	0	0	0	0	_	1	0	0.5	0.33	0.33	0	0	0	0	2.16
Sustainable Transport (ST)	0	0	0	0	0	0	_	0	0.5	0.33	0.33	0	0	0	0	1.16
Land Use efficiency (LUE)	0	0	0	0	0	0	0	_	0	0	0	0	0	0	0	0
Quality Built Environment (QBE)	0	0	0	0	0	0	0	0	_	1	1	0	0	0	0	2
Historic Environment & Cultural Heritage (HECH)	0	0	0	0	0	0		0	0	_	0	0	0	0	0	0
Natural Landscape (NL)	0	0	0	0	0	0	0	0	0	0	_	0	0	0	0	0
Biodiversity (B)	0	0	0	0	0	0	0	0	0	0	0	_	0	0	0	0
Water Resource (WR)	0	0	0	0	0	0	0	0	0	0	0	0	_	0	0	0
Flood Risk (FR)	0	0	0	0	0	0	0	0	0	0	0	0	0	_	0	0
Energy & Climate Change (ECC)	0	0	0	0	0	0	1	0	0.33	0.25	0.25	0	1	0	_	2.83
Diffusivity Score	0	0	0	0	1	2	4	1	3.99	3.41	4.16	0	1.33	2	0.5	–

social factors at a site level. However, design factors may also influence the importance of the natural environment, as the design of the space between buildings is a key component in the design of urban areas. In contrast to the other criteria, "Biodiversity" seems to be totally independent of everything else – the only one that scores 0 for both measures on influence.

This analysis also shows that though great effort has been made to achieve a highly integrated model, the degree of integration is far from satisfactory. The model is still unbalanced and the greater part of the model is highly compartmentalised. A lot of this is due to the nature of the sustainability criteria themselves rather than faults in the model, and that is partly due to the nature of the sustainability concept itself. However, the results can be used to review and further improve the model by identifying problem areas.

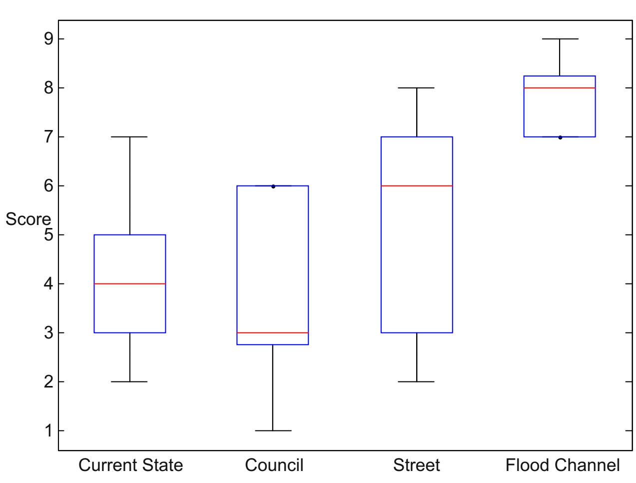

Fig. 7 – Experts' score variability for the sustainability criteria "Natural Landscape".

On a quantitative scale, there is a general trend for lower scores in the URSIM model assessment compared to the scores obtained from the expert assessment (Fig. 5a). However none of these differences are statistically significant and no conclusion can be drawn. There is also a large variation in the results of the expert assessment, as shown in the boxplot in Fig. 7 which depicts the variability of experts' score for the "Natural Landscape" criterion. This high variability in experts' scores leads to problems with consistency in classical assessment approaches.

3.3. *Exploratory SA tool*

Traditional perception-based qualitative SA of development plans can fail to provide proper feedback for optimum scenario development. For example, the perception of greenery and assessment of biodiversity often differ from what is actually on the site. Economic criteria are often viewed as paramount in decision making. However, an integrated assessment tool for SA with logical links to design variables can highlight important factors which might affect different sustainability criteria. Indeed, a carefully planned and managed urban river corridor can provide multiple social, environmental and economic benefits to society. Carefully designed buildings and open spaces will reduce the carbon footprint of urban areas, reduce flood risk, enhance community cohesion and stability, and improve both aquatic and terrestrial habitats and biodiversity. In addition, the potential economic benefits are considerable. Direct economic benefits occur through increased land prices, reduced costs associated with flooding, and reduced building running costs. Multiple indirect benefits can be achieved through the establishment of a happier and healthier society.

Theoretically the use of URSIM for optimum design development is possible because of the interconnection of different design variables to the sustainability criteria. It is possible that by optimising the value of different design variables an optimum design can be achieved. However this is not an easy process as many of the design variables in the models are qualitative in nature and it is often difficult to optimise them based on subjective perception. For example, the perception of safety is very difficult to optimise as a direct design variable. However, perception of safety is indirectly affected, among others design variables, by “level of activities”, “Active Frontage” and “% of empty property & derelict site” in URSIM. These variables are easy to quantify and can be used to influence perception of safety. This approach can be used to identify a number of modifications that enhance sustainability. These can then be incorporated into the final design, recognising the importance of addressing sustainability early in the design process (Boyko et al., 2006; Hunt et al., 2008). The stepwise structured model development approach provides the possibility to develop the integrated model at different levels of detail if more detailed information is needed (e.g. incorporating spatially explicit or more detailed design information).

Deciding upon the ‘best’ scenario following SA remains a contentious issue. An alternative is to carry out an integrated exploratory assessment. Our project has built a prototype of such a tool by linking the SA tool (URSIM) with 3D visualisation (Gill, 2013). By combining an interactive 3D design tool with a predictive decision support tool, the complementary strengths of both techniques are brought together. We have demonstrated that it is possible to feedback the SA of a design as part of the visualisation. Different designs can be developed by changing the value of design variables, which can simultaneously be visualised and tested for SA. Furthermore, it would be possible to use stakeholders to provide weightings for each sustainability objective, or to identify thresholds or minimum acceptable levels.

3.4. *Bringing Sustainability Appraisal into urban design*

Many years of research and constant campaigning have achieved significant legislative changes, with the result sustainability has now become the primary focus of the planning process. However, planning approaches are largely detached from Sustainability Appraisal models. SA is treated as an independent legislative requirement at the planning stage rather than a design support tool. This may be because the current SA models fail to provide any feedback to improve planning design and policy decision tools. The work described here is an attempt to make a more interactive tool, linking design with sustainability assessment.

Compartmentality analysis has highlighted that multidisciplinary science has mostly been founded upon the analysis of narrowly defined areas of research. However, work in the environmental, economic and social sciences is almost never concerned with isolated phenomena but with complex processes and relationships. This is particularly true in coupled socio-ecological systems, of which urban river corridors are a prime example. Understanding these complexities requires integrated approaches to research, such as that presented here. It is often impossible to make precise predictions concerning the development of coupled systems, and responses to their changes are usually not as precise as those for narrow fields. Nevertheless, studies that take into account such uncertainties are better attuned to reality, even though their results are more difficult to convey. Systems knowledge concerning the key problem areas will contribute to sustainability orientated actions.

A SA approach to cities takes environmental impact seriously, and gives it mainstream consideration while simultaneously asserting the value of social and economic progress. Thus the positive aspects of cities can be merged into a net benefit approach, where the enduring value of environmental improvement, social gain and economic enhancement can be seen as a joint legacy for the future. In the current economic situation, a positive sustainability agenda is needed to show that redevelopment of cities can be more sustainable and, at the same time, better opportunities are being created for people. The framework presented here can be equally useful for other parts of the world where there is no legislative requirement, but a broad consensus on the need for sustainable development exists.

4. Conclusion

A complex integrated Sustainability Appraisal model for urban planning and redevelopment was developed as a Bayesian Network. A set of sustainability criteria were refined and used in an expert appraisal, to assess the economic, social and environmental performance of alternative designs. Three scenarios were developed to examine alternative urban riverside designs, which were assessed by experts; their assessment logic was captured by structural knowledge elicitation and used to develop the URSIM integrated model. Sensitivity analysis helped to identify important design variables for each sustainability criteria and for each scenario. Modifications that enhance sustainability could then be incorporated into the final design. A fully integrated and interdisciplinary sustainability appraisal as presented here is beneficial compared to compartmentalised analysis when examining complex human-environment systems. Urban river corridors provide a prime example of such a situation.

Legal note

Please note that the scenarios are for research purposes only, have not been discussed with Sheffield City Council or the Environment Agency and do not indicate any likely outcome at the site.

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Annex-I. : Re-development scenarios

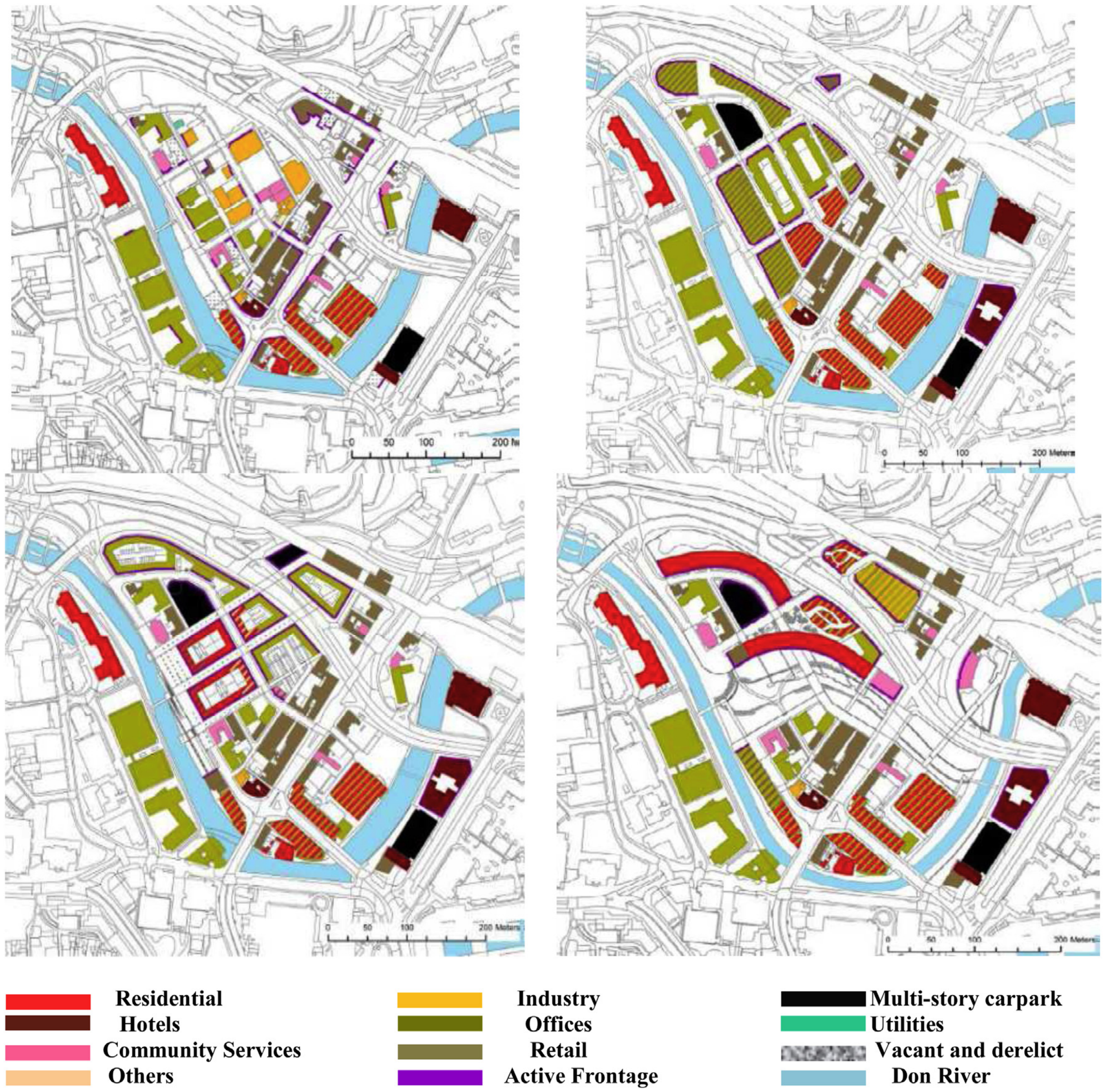

Fig. A-1. Land uses of four scenarios a.) The current (2009) situation, b.) *Council* scenario, c.) URSULA '*Street*' scenario, and d.) URSULA '*Flood Channel*' scenario (more information available at http://www.ursula.ac.uk/upload/Inner/Outputs/Info_pack.pdf). © Crown Copyright/database right 2011. An Ordnance Survey/EDINA supplied service.

Table A-1 – Key features and differences between the three re-development scenarios

	Sheffield city Council/ Environment Agency	URSULA 'Street'	URSULA 'flood channel'
General layout	New buildings replace existing and vacant spaces. New public green space by river.	Built form organised around hard landscaped urban squares and streets planted extensively with trees.	Built form structured around an open space (flood channel), allowing water to periodically invade the urban environment.
Typology	Conservation of existing block and street structure	Slight modification of street/block structure to multiply access to the river	Destruction of street and block structure to make space for water
Relationship with the river	Terraced pocket park along large stretch of waterfront, providing closer interaction and direct access to the river.	Amenity space created on riverside with direct access to water. Urban squares at higher level provide spaces for outdoor terraces.	No direct access to the river but some public green space next to river.
Flood risk	Managed by constructing walls, dredging and widening river channel, and removing bankside trees.	Managed by constructing a linear low wall along the waterfront, complemented by deployable barriers.	Flood channel designed to carry water from a 1 in 5 year flood event. In addition: walls, deployable barriers and buildings to be flood resilient.
River management	Fish/canoe ramp built into existing weir. Trees and sediment banks along the river have been removed.	A rock ramp is constructed on the existing weir. Trees and sediment banks along river have been retained.	Weir removed entirely. This will lower water levels, providing increased habitat for riverine biodiversity.
Buildings and uses	Standard high density buildings, dominated by offices	A diversity of built forms and functions. Building height decreases towards the river to improve microclimate.	Innovative buildings following latest technologies in sustainability including energy efficiency and built to be resilient to flooding.
Open spaces and vegetation	Mixture of hard and soft landscape	Mainly hard urban landscape	Mainly soft landscape and water
Integrated Urban Water Management	Traditional drainage through pipes to sewers with some green roofs.	Rain water absorbed through green roofs, tree pits, and permeable paving.	Capturing rain water in ponds and the new flood channel.

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