**SEVENTH FRAMEWORK PROGRAMME**
**THEME 6: Environment (including climate change)**

**Contract for:** **Collaborative Project**

# *D.6.1*
# *DSS Design Report*

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# 1. Introduction

## 1.1 Purpose of the document

This document is the D.6.1 Design Report. The **aim of this document** is to describe the BRIDGE Decision-Support System (DSS) design procedure and the selection of the appropriate software platforms and tools to be used in the DSS. Both the conceptual and the technical design of the BRIDGE DSS are described in this document. The main achievement and innovation of BRIDGE are based on the development of a DSS which reflects the multidimensional nature of the urban metabolism, as operationalised in comprehensive and transferable indicators easily understood by urban planners.

## 1.2 Document Structure

**Chapter 1** is the introduction of the document (current chapter) which includes: the purpose of the document, the document's organization, the list of definitions and acronyms used in this document, the list of applicable and referenced documents and the BRIDGE project overview.

**Chapter 2** is an overview of the BRIDGE DSS providing the Guidelines both for the Conceptual and the Technical design.

**Chapter 3** specifies the Conceptual Design of the System.

**Chapter 4** specifies the System Architecture.

## 1.3 Definitions and acronyms

### *Acronyms*

| | |
|---|---|
| AHP | Analytical Hierarchy Process |
| BRIDGE | sustainaBle uRban plannIng Decision support accountinG for urban mEtabolism |
| CA | Cellular Automata |
| CoP | Community of Practice |
| DSS | Decision Support System |
| DTM | Digital Terrain Model |
| GIS | Geographic Information Systems |
| GUI | Graphical User Interface |
| MCA | Multi-Criteria Analysis |
| MCE | Multi-Criteria Evaluation |
| PSS | Planning Support System |
| SDSS | Spatial Decision Support System |
| SHP | Shapefile |

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## 1.5 Project Overview

This overview is an introduction to the BRIDGE Project. Who is familiar with the Project can skip this section because its content is already known.

Urban metabolism considers a city as a system and distinguishes between energy and material flows. “Metabolic” studies are usually top-down approaches that assess the inputs and outputs of food, water, energy, etc. from a city, or that compare the metabolic process of several cities. In contrast, bottom-up approaches are based on quantitative estimates of urban metabolism components at local scale, considering the urban metabolism as the 3D exchange and transformation of energy and matter between a city and its environment. Recent advances in bio-physical sciences have led to new methods to estimate energy, water, carbon and pollutants fluxes. However, there is poor communication of new knowledge to end-users, such as planners, architects and engineers.

BRIDGE aims at illustrating the advantages of considering environmental issues in urban planning. BRIDGE will not perform a complete life cycle analysis or whole system urban metabolism, but rather focuses on specific metabolism components (energy, water, carbon, pollutants). BRIDGE’s main goal is to develop a Decision Support System (DSS) which has the potential to propose modifications on the metabolism of urban systems towards sustainability [R1].

BRIDGE is a joint effort of 14 Organizations from 11 EU countries. Helsinki, Athens, London, Firenze and Gliwice have been selected as case study cities. The project uses a “Community of Practice” approach, which means that local stakeholders and scientists of the BRIDGE meet on a regular basis to learn from each other. The end-users are therefore involved in the project from the beginning. The energy and water fluxes are measured and modeled at local scale. The fluxes of carbon and pollutants are modeled and their spatio-temporal distributions are estimated. These fluxes are simulated in a 3D context and also dynamically by using state-of-the-art numerical models, which normally simulate the complexity of the urban dynamical process exploiting the power and capabilities of modern computer platforms. The output of the above models lead to indicators which define the state of the urban environment. The end-users decide on the objectives that correspond to their needs and determine objectives’ relative importance. Once the objectives have been determined, a set of associated criteria are developed to link the objectives with the indicators. BRIDGE integrate key environmental and socio-economic considerations into urban planning through Strategic Environmental Assessment. The BRIDGE DSS evaluates how planning alternatives can modify the physical flows of the above urban metabolism components. A Multi-criteria Decision Making approach has been adopted in BRIDGE DSS. To cope with the complexity of urban metabolism issues, the objectives measure the intensity of the interactions among the different elements in the system and its environment. The objectives are related to the fluxes of energy, water, carbon and pollutants in the case studies. The evaluation of the performance of each alternative is done in accordance with the developed scales for each criterion to measure the performance of individual alternatives.

Several studies have addressed urban metabolism issues, but few have integrated the development of numerical tools and methodologies for the analysis of fluxes between a city and its environment with its validation and application in terms of future development alternatives, based on environmental and socio-economic indicators for baseline and extreme situations. The innovation of BRIDGE lies in the development of a DSS integrating the bio-physical observations with socio-economic issues. It allows end-users to evaluate several urban planning alternatives based on their initial identification of planning objectives. In this way, sustainable planning strategies will be proposed based on quantitative assessments of energy, water, carbon and pollutants fluxes.

## 1.6 Decision Support Systems in Urban Planning

**Environmental management** has become increasingly complex in recent decades, with higher demands for consideration of multiple environmental, social and economic factors. In line with this, the environmental management industry has become increasingly sophisticated in the use of technology, as more stakeholders become involved, better tools are developed and requirements for openness and accountability increase. The nature of the problems addressed by environmental managers is complex, ranging across both temporal and spatial scales. These requirements have spawned a variety of models over the years, and modeling systems are increasingly used within environmental management for assisting with compliance and assessment processes, as well as enhancing, understanding and informing decision-making.

Traditionally, the functional parts of the urban context are analyzed within distinct research disciplines. The different groups of decision-makers in urban planning processes use different decision-making techniques and follow different interests. In order for the evaluation outcomes to be supported, the decision-makers need to describe the problem and solve it in a structured way. In the light of such competing demands, powerful decision-making tools are needed to comprehensively analyze baseline information as well as to satisfy multiple-period, multiple-objective, and multiple-user requirements [R1].

DSSs are capable of supporting complex decision making and of solving semi-structured or unstructured problems through a computer interface that presents results in a readily understandable form. According to Böhner [R3]: A **DSS** is a computer based information system intended to help decision-makers compile useful information to identify problems, assess them and help in making decisions. DSS have been developed to introduce multiple inter-disciplinary aspects into the planning process in such a complex decision environment. These systems:

- aim at helping decision makers in finding concrete solutions for decision problems;
- focus on supporting rather than replacing the user’s decision-making skills;
- facilitate the use of data, models in decision making; and
- are used to support semi-structured and unstructured decisions.

**Since the early 1970s**, DSS technology and applications have evolved significantly. Many technological and organizational developments have exerted an impact on this evolution. DSS once utilized more limited database, modelling, and user interface functionality, but technological innovations have enabled far more powerful DSS functionality. DSS once supported individual decision-makers, but later DSS technologies were applied to workgroups or teams, especially virtual teams. The rising pressure for urban sustainability confronts planners with the necessity of taking into account the environmental and socio-economic considerations at once, as well as their potential impacts typically analyzed by other disciplines. Therefore, specific evaluation methods and tools need to be integrated to address multiple inter-disciplinary aspects within decision-making regarding urban planning [R4].

Cowen [R5] was among the first researchers to publish an article in 1988 that defines GIS in terms of a decision support system. He recognized that all aspects of GIS in some way assist with decision making and effectively provide support in decision. This purpose has been adopted as a popular way to describe GIS usage, no matter what kind of application one considers.

The basis of geospatial decision support is the GIS technology. The basic decision supports of GIS include data management to extend human memory, graphic display to enhance visualization, and spatial analysis functions to extend human computing performance. Beyond these common GIS decision aids, special features include modeling, optimization, and simulation functions required to generate, evaluate, and test the sensitivity of computed solutions. Other functions, such as statistical, spatial interaction, and location/allocation models, can also be supported by GIS software. Such decision support models linked with GIS linked to environmental models and decision making models used for evaluation of land planning decisions often called **spatial decision support systems (SDSS)** [R6]. As SDSS development was moving forward, developments involving planning support systems (PSS) were getting under way [R7]. The focus was on how to make use of decision support capabilities incorporating GIS and analytic models in a planning context. PSS developments are related to the GIS-based activity, but PSS have been conducted mostly in the context of planning for groups.

As most territorial and environmental assessments involve several alternative options and numerous stakeholders with different views and perceptions SDSSs provide effective techniques to assess cumulative impacts and to carry out a vulnerability or suitability analysis in order to evaluate alternatives.

Broadly speaking, a SDSS is an interactive, computer-based system designed to support a user or group of users in achieving a higher effectiveness of decision making while solving a semi-structured spatial problem. It is designed to assist and guide planners in making spatial planning decisions. In general, these systems allow environmental data and economic and social elements to be considered simultaneously. Furthermore, all the aspects involved in the decision can be spatially compared and the final results can be represented by means of specific maps, which ensure a very effective support for the development of the decision-making process.

The operational functionalities of a SDSS can for the analytical purpose be subdivided into (1) data management, (2) models (including both simulation and decision models), and (3) presentation of results and scenarios. Given the remarkable advancements in GIS technologies, the mainstream developments in the field of SDSSs usually take the path of coupling and integrating, in one way or another, GIS and DSS. Therefore, the tasks taken on by these two in terms of the three fundamental operational functionalities mentioned above can schematically be represented as in Figure 1. The answer to the question of how to integrate GIS and DSS is SDSS, given that most relevant simulation models are already spatially oriented. These operational, methodological and technical issues and problems are precisely what BRIDGE DSS wants to address, within its specific scope and focus on urban metabolism.

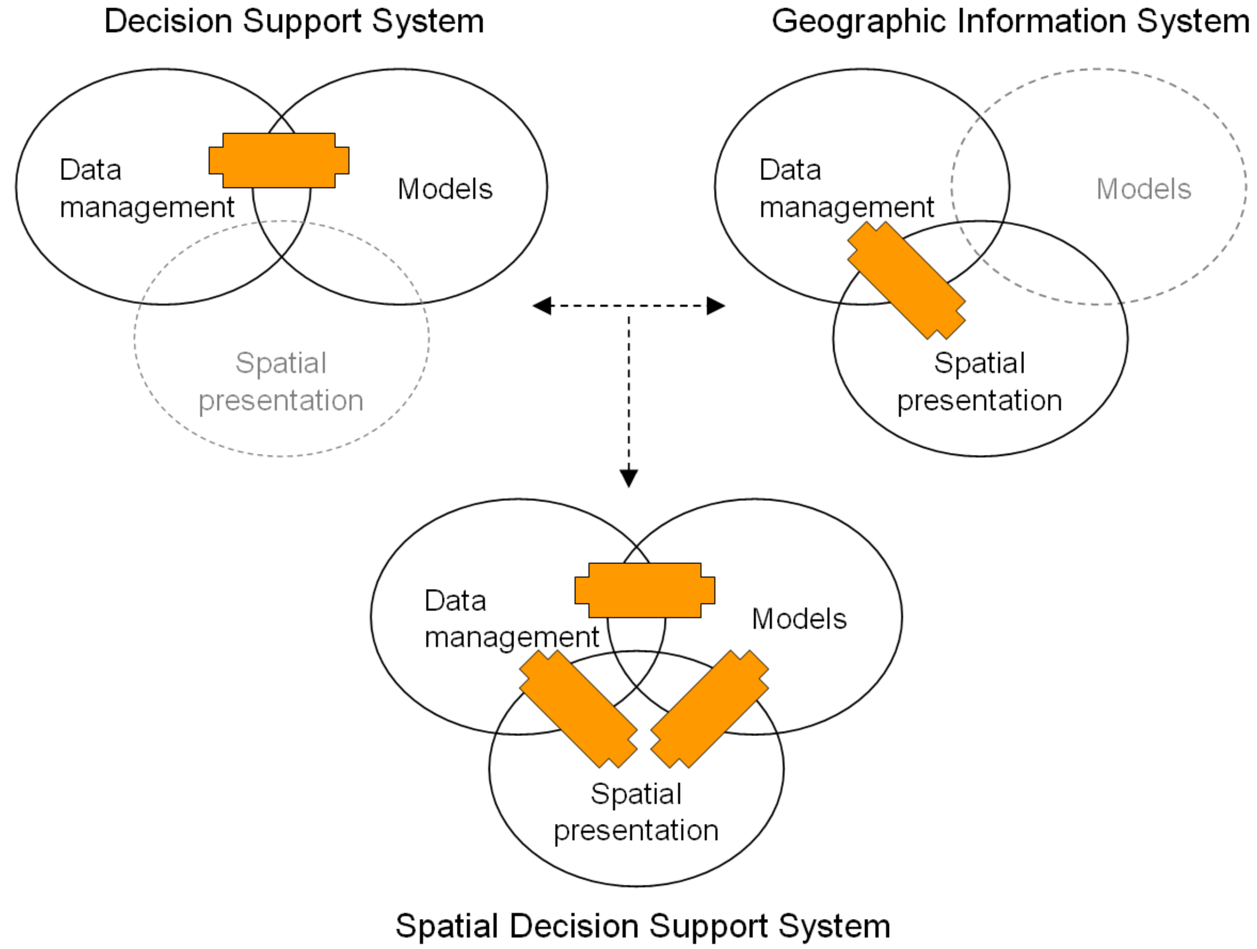


**Figure 1.** DSS-GIS-SDSS

Figure 2 describes a more customarily used model of the decision-making process in a DSS environment. Once the problem is recognized, it is defined in terms that facilitate the creation of models. Alternative solutions are created, and models are then developed to analyze the various alternatives. The choice is then made and implemented. Of course, no decision process is this clear-cut in real situations [R15].

The main aim of the BRIDGE DSS is to assist decision-making by providing a structured assessment of alternatives and methods for the comparative analysis, ranking, and selection among them. The problem with selecting options is always that options depend on the objectives that the decision-maker states (end-user). The objectives are usually conflicting, and therefore, the solution must be seen as the trade-off between a number of objectives which in turn depend on the preferences of the decision-makers. The main function of the BRIDGE DSS is to provide the tools for the evaluation of alternatives based on key urban metabolism components.

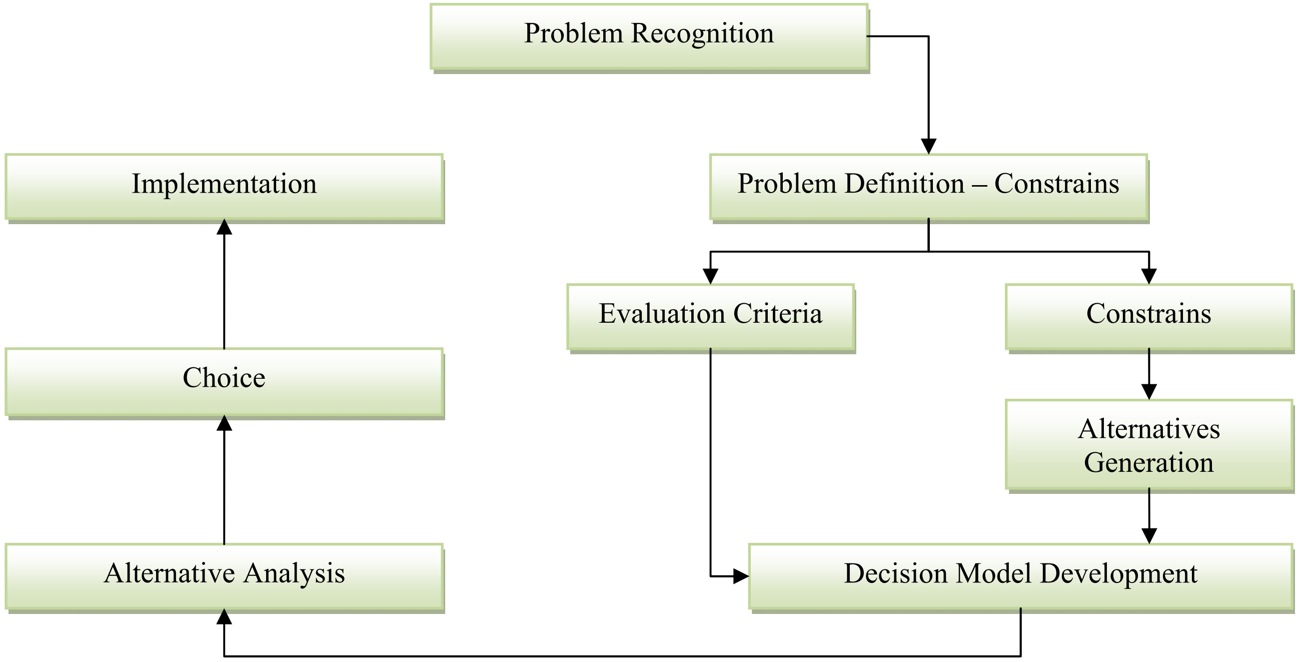


**Figure 2.** The DSS decision making process [R4], [R15].

# 2. Guidelines for System Analysis and Design

## 2.1 General Guidelines

The **most important processes**, supported by the BRIDGE DSS, include:

- Storage, processing, and presentation of data required continuously, repeatedly or even once in relation with the specific problem.
- Presentation and user-transparent description of simple and complex relations between data inputs relevant to the decision process.
- Modeling and simulation of impacts deriving from desired, proposed and/or existing alternative solutions.

**Urban metabolism** is considered as the exchange and transformation of energy and matter between a city and its environment. The city is considered as a system and the physical flows between this system and its environment will be quantitatively estimated in the framework of the project. BRIDGE focuses on the following components of urban metabolism:

- Energy.
- Water Balance.
- Carbon and pollutants ($SO_2$, $NO_x$, CO, $CO_2$, $O_3$, $PM_{10}$, $PM_{2.5}$).

The challenges of the sustainable urban planning with regards to the above components are:

- Energy
  - ✓ Optimize energy efficiency of the urban structure.
  - ✓ Minimize energy demand of settlements.
  - ✓ Maximize efficient use of energy through building services and energy supply.
  - ✓ Maximize share of renewable energy sources.
  - ✓ Maximize the use of eco-friendly and healthy building materials
- Water
  - ✓ Minimize primary water consumption.
  - ✓ Minimize impairment of the natural water cycle.
- Carbon and pollutants
  - ✓ Minimize the emissions to the atmosphere.
  - ✓ Maximize pollutants sinks.

The BRIDGE DSS is a standardized approach to measure and address these key factors, which shape the way in which urbanization affects the natural environment and the socio-economic activities of inhabitants. Its development and application will encompass participatory CoP meetings, where local stakeholders will contribute to the methodology, to the definition of objectives, criteria and indicators and to provide alternatives. The BRIDGE DSS evaluates how planning alternatives can modify the physical flows of the above urban metabolism components. To cope with the complexity of urban metabolism issues, the objectives measure the intensity of the interactions among the different elements in the system and its environment.

## 2.2 Guidelines to conceptual design

The main goal is to determine how the urban metabolism can be modified towards sustainability. The DSS will be based on **objectives** related to the principal environmental and socio-economic components of urban metabolism (in relation to energy, water, carbon and pollutants). The objectives must reflect the intensity of the interactions among the different elements in the urban system and its environment, and must allow an assessment of the urban system regarding its sustainability. These objectives have to reflect three main aspects, namely environmental, economic and social. These objectives, which correspond to the users' needs, and their relative importance (weighting the objectives) will be decided through the framework of CoP.

Once the objectives have been determined, a set of associated **criteria** need to be developed. These criteria are selected to provide a link between the objectives and the indicators and usually have time limits and/or thresholds associated with. Objectives will be translated into specific criteria.

The BRIDGE DSS relies on **indicators** as inputs and they should demonstrate the level of achievement of each criterion, in a quantified manner. It is intended that indicators can reflect the multidimensional nature of the urban metabolism, and also be easily understood by a non-scientific public. The main limitation in their selection is data availability.

An example of objectives, criteria and indicators is shown below in Table 1.

**Table 1.** Example of objectives and indicators

| Objectives | Criteria | Indicators |
|---|---|---|
| Improve Air Quality | EU Thresholds | Concentration of pollutants (Ozone & PM) |
| | Overall reduction | Transport emissions and split per type (public/private) |
| Optimize Energy Consumption | Reduction of current rates | Energy demand (consumption per dwelling) |
| | 38% of total | Percentage of energy from renewable sources |
| Protect the Water Balance | Reduction of surface run-off and maximum filtration (aquifer recharge) | Water balance: precipitation, surface run-off, evapotranspiration, filtration, and flooding events. |
| Enhance human well-being | EU Threshold (0%) | Population exposure to air pollutants |

## 2.3 Guidelines to technical design

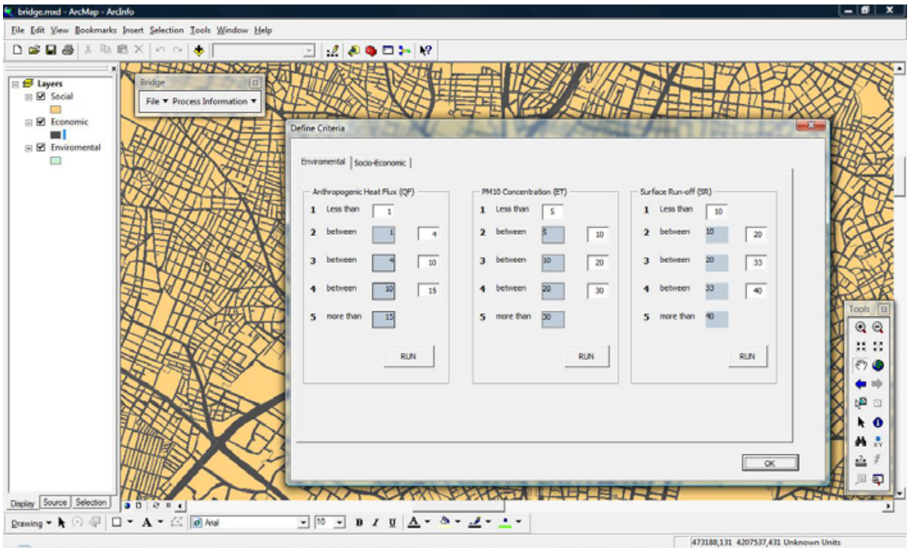
The strong spatial connotations of urban planning impose the use of Geographic Information System (GIS) in DSS development. A GIS captures, stores, analyzes, manages, and presents data that is linked to a geographic location. Planning alternatives refer to different options concerning the projects, proposed by the decision makers and will be analyzed by the BRIDGE DSS.

The use of GIS allows for solid, spatially-referenced data serve as a fact-based foundation for the decisions that need to be made to ensure a sustainable future for the urban environment. However, the reality is that the tools and methodologies currently being developed through academic and private research rarely reach the hands of the decision-makers that deal with these issues everyday [R8].

The BRIDGE DSS framework is composed of the following modules:

- The GIS that is used to integrate all datasets, analyze the various spatial entities, prepare the data for the models, store the results and then visualize them.
- The "on-line" models, which will be used to simulate the results of various actions.
- The interfaces between the GIS and "on-line" models.
- The communication modules between the GIS and the "off-line" models, meaning the integration of the "off-line" models outputs.
- The impact assessment methodologies for evaluating the environmental and socio-economic impacts of urban metabolism.
- The Multi-Criteria Evaluation (MCE) module, which will have the role of the middleware.
- The Graphical User Interface (GUI), which integrates all other components in one integrated system and hides the intricacies of the system for the user.

The user will use the GUI to define the alternatives, the weights for objectives that will be used to provide the scores as shown in Figure 3. A report will also be produced with the results of the analysis.



| | Anthropogenic Heat Flux (QF) | | PM10 Concentration (ET) | | Surface Run-off (SR) | |
|---|---|---|---|---|---|---|
| 1 Less than | 1 | | 5 | | 10 | |
| 2 between | 1 | 4 | 5 | 10 | 10 | 20 |
| 3 between | 4 | 10 | 10 | 20 | 20 | 33 |
| 4 between | 10 | 15 | 20 | 30 | 33 | 40 |
| 5 more than | 15 | | 30 | | 40 | |

**Figure 3.** Example of criteria scaling (i.e. establishment of targets) in a mock-up of BRIDGE DSS

# 3. Conceptual Design

This chapter is a description of the BRIDGE DSS Conceptual Design. The main overview of the BRIDGE DSS is described along with Multicriteria Evaluation (MCE) and Cellular Automata (CA) techniques that will be used. An example illustrating the main outline of the BRIDGE DSS is also presented.

## 3.1 System Overview

The development of BRIDGE DSS is based on an **analytical** and a **design component**, linking the bio-physical processes in urban environment with socio-economic parameters in order to estimate the environmental and the socio-economic impacts (positive and negative) of urban metabolism components. BRIDGE will estimate the urban metabolism by means of physical fluxes of energy. water, carbon and pollutants to and from the urban surface. The analytical component will support the assessment of the environmental impacts of the above fluxes, while the design component will offer tools to assess different planning alternatives. These planning alternatives are practically modifications of land use and resource and therefore modifications of the metabolism of the urban system. The link between the analytical and the design components is a MCE module to supplement decision support capabilities. This module will combine the environmental with the socio-economic aspects of urban metabolism and will evaluate the performance of each planning alternative in terms of sustainability.

The conceptual illustration of the BRIDGE DSS is shown in Figure 4. The environmental impacts of urban metabolism for given urban structures and given levels of resource use in the BRIDGE case studies will be addressed using the **analytical component**. The physical flows will be identified using numerical modeling and sets of indicators will be produced, according to the urban sustainability objectives. This component is foreseen to have four major functions for analyzing energy, water balance, carbon and air pollutants flows and providing indicators which will reflect the current state of the urban environment, in each case study, as well as the environmental pressures (or benefits) that every planning alternative will cause.

In **MCE module** the environmental indicators will be combined with socio-economic indicators using a Multi-Criteria Analysis (MCA) approach. The latter will be derived by combining the environmental information provided by the analytical component with socio-economic variables that will be stored in the DSS databases, reflecting the socio-economic status of each case study, or the respective modifications that every planning alternative will bring out. Examples of such socio-economic variables are the spatial distribution of population, the employment, the cost of planning interventions, etc. Both environmental and socio-economic indicators will at first be evaluated according to specific criteria that will have been set for each indicator as it was described in the previous Section. A score for each indicator will be resulted from this evaluation. The scoring scales will be predefined, but the end-users will be able to modify them if needed. The end-users will be also being asked to provide information about the criteria weights (that is determine the significance of the criteria according to their preferences).

The **design component** will be used to handle and present modified land use arrangements and practices for resource use on the basis of different planning alternatives at specific sites of planning interventions in BRIDGE case studies. These planning alternatives will be provided by the end-users. The change in land uses will be handled in two scales. In the local scale, the planning alternatives provided by the end-users will already include estimations of their impact on strictly local land use changes. The modifications that they will cause to urban metabolism will be assessed by the analytical component on the basis of the estimation of changes in energy, water, carbon and pollutants fluxes. In a broader (neighborhood or city) scales, these local land-use scenarios will be used as inputs for a **CA** model included in the design component, to simulate broader and long-term land use changes. The broader scale scenarios, thus obtained, can subsequently be used to assess future environmental impacts on the basis of physical flows modifications that will be simulated by the numerical models included in the analytical component. Finally, this information will be exploited by the DSS to assess and evaluate strategic scenarios for urban sustainability.

The BRIDGE DSS will provide quantitative assessments of the environmental impacts of reducing air pollution, slowing storm-water runoff, conserving energy, etc. Moreover it will relate these environmental impacts to economic benefits for the community. This subsequently leads to a process of alternating use of both DSS components, which usually starts with the assessment of the current or proposed situation, and then continues with the exploration of alternatives. The physical flow models that included in the analytical component have been described in detail in Deliverable D.5.1 (Model Selection Report). The main parts of MCE module and design component are described in the following Sections.

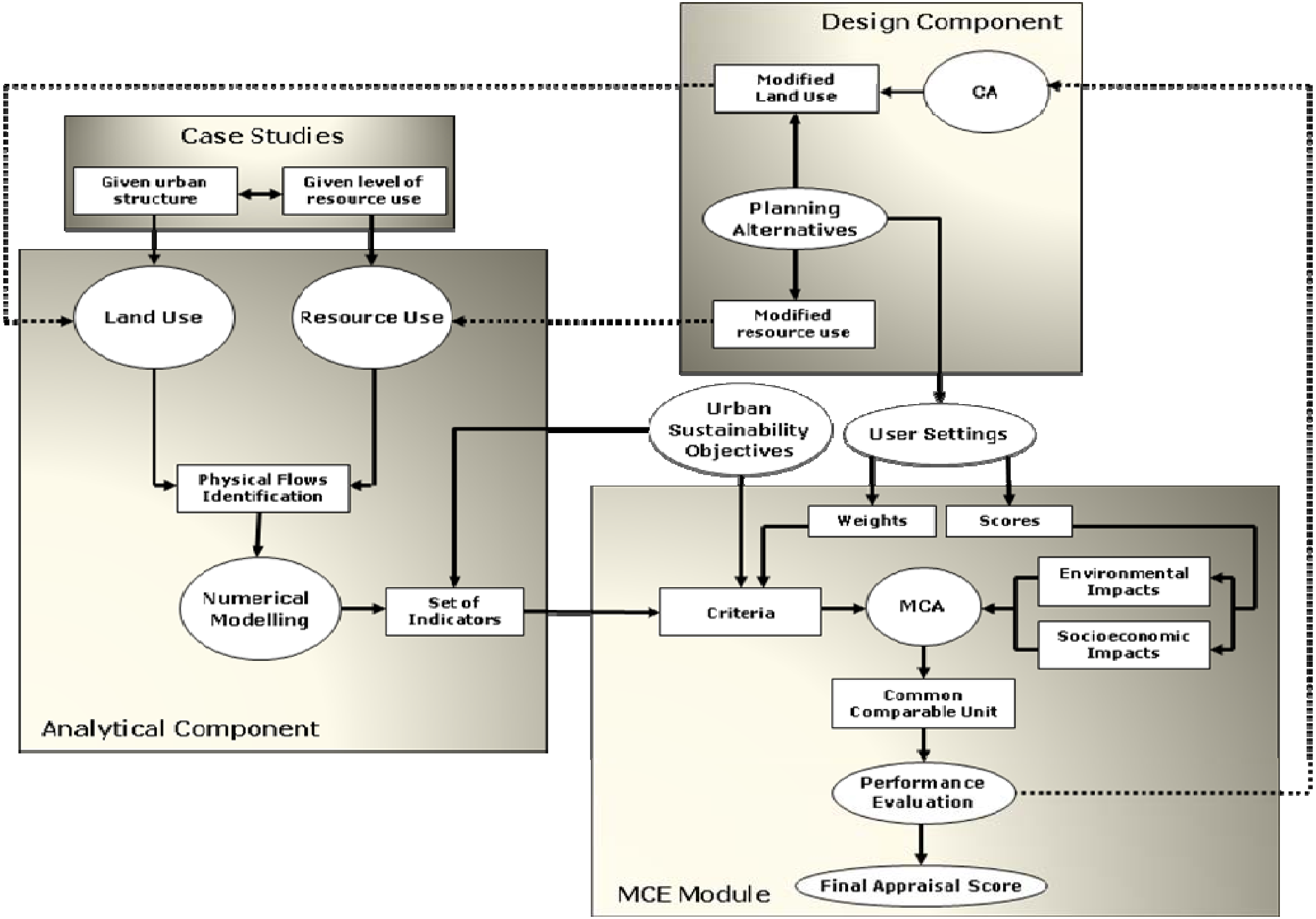


**Figure 4.** Conceptual illustration of the BRIDGE DSS

## 3.2 Multi-Criteria Evaluation

Urban planning using **Multi-Criteria Analysis** (MCA) has attracted the attention of decision makers for a long time. The methods can provide solutions to increasing complex environmental management problems. Traditional single criteria decision making is normally aimed at maximization of benefits with minimization of costs. The MCA facilitates a combined assessment of multiple issues, provides better understanding of inherent features of a decision problem, promote the role of participants in decision making processes, facilitate compromise and collective decisions and provide a good platform to understand the perception of models in a realistic scenario. MCA methods promote informed decisions by providing holistic, comprehensive and robust information. Negotiation, quantification and communication are also facilitated by these methods.

Multi-Criteria Decision Making is a branch of a general class of operation models which deal with decision problems under the presence of a number of decision criteria. There are several Multi-Criteria Decision Making methods: priority based, outranking, distance based and mixed methods. Each method has its own characteristics and the methods can also be classified as deterministic, stochastic and fuzzy. These methods share common characteristics of conflict among criteria, incomparable units, and difficulties in the selection of alternatives. The best alternative is usually selected by making comparisons between the different alternatives in respect to each attribute.

A **Multi-Criteria Evaluation (MCE)** technique will be used in the BRIDGE DSS, as a middleware to the analytical and the design component. A framework of the MCE technique, corresponding to the evaluation of planning alternatives, can be seen as a seven-step procedure [R9]:

1. The users state the main goal (e.g. sustainability) and decide on the objectives to cover their needs, which will be subsequently connected to specific criteria and indicators;
2. The measurement scales for objectives and indicators are selected;
3. The users define the planning alternatives;
4. The users determine the objectives' relative importance (weighting the objectives);
5. The performance of the alternatives is evaluated using a Multi-Criteria Decision Making method, by determining scores for each alternative using the measurement scales defined in step 2;
6. Aggregate the scores into several overview presentations;
7. Analyze the results and inform the decision maker.

MCE involves transformations of available data, which characterize impacts of decision alternatives, resulting in a summary score. The idea of computing a summary score is to provide one measure used as the basis for rank ordering of decision alternatives from best to worst. Three types of data transformations are common to each MCE technique: normalization of data to a common scale, transformation of decision maker preferences into numeric weights and aggregation of normalized data with numeric weights into a common measure of intrinsic value—a summary score. All three data transformation will be performed in the framework of the MCE module of BRIDGE DSS. Information on implementing these transformations are included in the following sections.

## 3.3 Normalization of Indicators to a common scale

In MCE, the attributes that are characteristic of decision alternatives and have known preference order of attribute values are used as the bases for evaluating the alternatives. The preference order means that, for example, a high attribute value is deemed to be better than the medium attribute value, which is in turn considered still better than the low attribute value; or, conversely, as in the case of a cost-related attribute for example, a low attribute value is deemed to be better than medium and high attribute values.

In the BRIDGE DSS the evaluation attributes are the values of indicators. The values of indicators computed by the models for each alternative have to be normalized to a common scale. There are various normalization approaches that can be followed and different normalization methods can be applied to different indicators [R15]. Three approaches will be explained below: the binary, the linear and the nonlinear.

The binary approach assumes of a threshold exist for an indicator. In some cases thresholds like this are derived from legislation (European or national). In some other cases the A value above the threshold is considered as acceptable and below the threshold unacceptable. The advantage of this approach is its simplicity, both in implementing and also in interpreting the results.

The linear approach produces proportional transformations of the values of indicators. The simplest formula is the “maximum score” procedure which divides each value by the maximum value:

$$x_{ij}^{'} = \frac{x_{ij}}{x_j^{\max}}$$

where $x_{ij}^{'}$ is the standardized score for the ith alternative and the jth criterion, $x_{ij}$ is the value of the indicator and $x_{ij}^{\max}$ is the maximum score for jth criterion. In the case criteria where the lower the raw data value, the better the performance, (cost criteria for example) the following formula for linear scale transformation can be used:

$$x_{ij}^{'} = 1 - \frac{x_{ij}}{x_j^{\max}}$$

The linear approach can be applied to normalize some indicators in BRIDGE DSS. It is not obligatory to use the same approach to normalize all indicators. A different normalization method can be applied to different indicators.

In the nonlinear normalization procedure, the normalized value is computed for the indicator by dividing the difference between a given indicator value and the minimum value of the value range:

$$x_{ij}^{'} = \frac{x_{ij} - x_j^{\min}}{x_j^{\max} - x_j^{\min}}$$

For the cost indicators, the normalized score is computed by dividing the difference between the maximum value and a given value from the value range:

$$x_{ij}^{'} = \frac{x_j^{\max} - x_{ij}}{x_j^{\max} - x_j^{\min}}$$

The advantage of nonlinear approach is that the normalized values range precisely from 0 to 1. The disadvantage is that this procedure does not keep the proportionality between the raw values and the normalized ones.

Both linear and non-linear approaches can be used to normalize different indicator values. A user-defined value function is possible to be used for normalization.

## 3.4 Transform preferences into weights - Pair-wise comparison

An important step in the MCE procedure is the articulation of the user's preferences in regard to criteria. The uneven importance of criteria may result from policies, established hierarchies, cause–effect relationships, and often subjective preferences. The preferences are expressions of one's values and in the MCE context represent the varying degrees of importance assigned to criteria. A common means of representing the user's preferences are weights. Weight is a numeric amount assigned to an evaluation criterion, indicating its importance relative to other criteria in the decision situation. The weights are usually normalized, so that their sum for all n-criteria considered in a given decision situation equals 1. The larger the weight, the more important a given criterion is. It is important to understand that weights are influenced by differences in the range of variation in each criterion. The range of criterion value variation will highly influence the importance assigned to a criterion.

There are various procedures for transforming users preferences into numerical weights and among them are ranking, rating, pair-wise comparison, etc. In BRIDGE DSS the method to transform the users' preferences into criteria weights is the pair wise comparison.

Pair wise comparison was developed by Saaty [R11], as part of a multi-criteria decision making method called Analytical Hierarchy Process (AHP). The essence of the process is decomposition of a complex problem into a hierarchy with a goal at the top of the hierarchy, criterions and sub-criterions at levels and sub-levels of the hierarchy, and decision alternatives at the bottom of the hierarchy. The "criterions" and "sub-criterions" are translated into "objectives" and "criteria" in the sense of the terms used in BRIDGE (Figure 5).

Elements at a given hierarchy level are compared in pairs to assess their relative preference with respect to each of the elements at the next higher level. The verbal terms of the Saaty's fundamental scale is used to assess the intensity of preference between two elements. Ratio scale and the use of verbal comparisons are used for weighting of quantifiable and non-quantifiable elements. The method performs computation until the composite final vector of weight coefficients for alternatives is obtained. The entries of final weight coefficients vector reflect the relative importance (value) of each alternative with respect to the goal stated at the top of hierarchy [R11].

The pair-wise comparison technique comprises taking pairs of objectives and asking two questions: (1) which criterion is more important: $C_i$ or $C_j$ and (2) how much is the more. The answers are given by a 1-9 scale developed by Saaty [R11]. A square, reciprocal matrix A is then generated. Element $a_{ij}$ is the weight given by user for objective i compared to j. Table 2 shows the meaning of the scale values that are used in the pair-wise comparison. If for example a user thinks that to improve energy efficiency ($C_1$) is strongly more important that to protect the water balance ($C_2$) in his case, then element $a_{ij}$ will have the value of 7. The diagonal of matrix A is 1 (because each objective is the same importance with itself) and $a_{ji} = \frac{1}{a_{ij}}$.

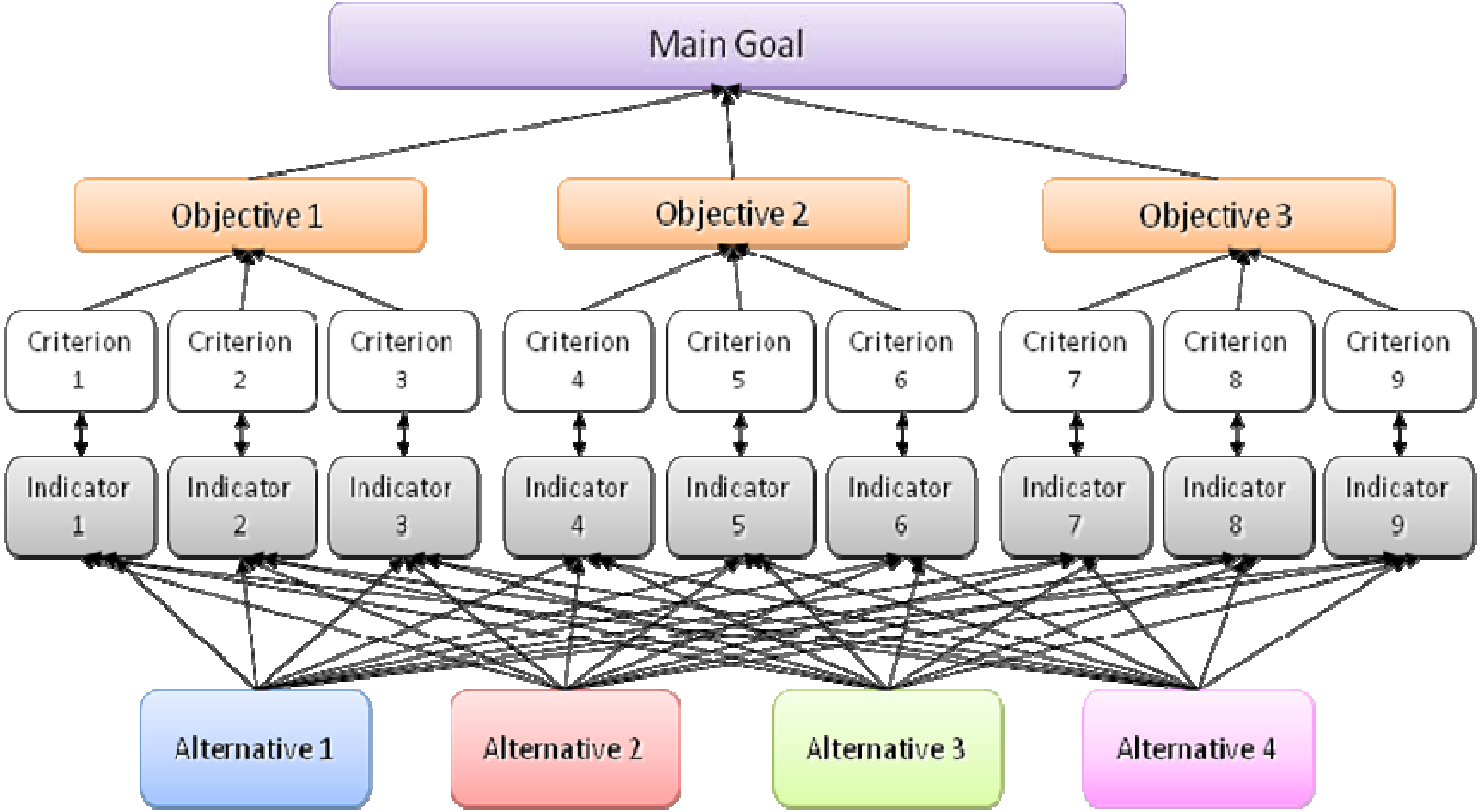


**Figure 5.** Basic structure of BRIDGE objectives, criteria and indicators hierarchy

The matrix A can be presented as follows:

$$A = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ 1/a_{12} & 1 & \dots & a_{2n} \\ \dots & \dots & 1 & \dots \\ 1/a_{1n} & 1/a_{2n} & \dots & 1 \end{bmatrix}$$

**Table 2.** Scale value meanings for pair-wise comparison

| | |
|---|---|
| 1 | same importance |
| 2 | slightly more important |
| 3 | weakly more important |
| 4 | weakly to moderate more important |
| 5 | moderately more important |
| 6 | moderately to strongly more important |
| 7 | strongly more important |
| 8 | greatly more important |
| 9 | absolutely more important |

The weights w are now computed following the procedure below:

- Estimate the maximum eigenvalue $\lambda$ of matrix A – $\det(A - \lambda I) = 0$
- Find the eigenvectors $w$ of matrix A – $(A - \lambda I)w = 0$
- Normalize $w$ to $\tilde{w} - \tilde{w}_i = \dfrac{w_i}{\sum_{j=1}^{n} w_j}$

Because individual judgments never agree perfectly, the degree of consistency achieved in the ratings is measured by a consistency ratio indicating the probability that the matrix ratings were randomly generated. The rule of thumb is that a consistency ratio less than or equal to 0.10 indicates an acceptable reciprocal matrix A, and ratios over 0.10 indicate that the matrix should be revised. Revising the matrix comes down to (1) finding inconsistent judgments regarding the importance of criteria, and (2) revising these judgments by comparing again the pairs of criteria judged inconsistently. To compute the consistency ratio the below procedure is followed:

- Determine the weighted sum vector $ws = A \cdot \tilde{w}$
- Determine the consistency vector $CV = ws \div \tilde{w}$
- Compute the average value of the consistency vector $\mu = \dfrac{\sum CV}{n}$

- Compute the consistency index $CI = \frac{\mu - n}{n-1}$.

  The calculation of CI is based on the observation that μ is always greater or equal to the number of criteria (n), and μ = n if the pair-wise comparison matrix A is a consistent matrix. Accordingly, μ – n can be considered as a measure of the degree of inconsistency. Consistency index is a measure of departure from consistency.

- Compute the consistency ratio $CR = \frac{CI}{RI}$, where RI is the random index representing the consistency of a randomly generated pair-wise comparison matrix. Tabulated values of RI can be found in the AHP literature [R11]. The value of RI depends on the number of criteria being compared. The value of CR below the threshold value indicates consistency.

## 3.5 Decision Rule

A decision rule is a procedure for ordering alternatives from most to least desirable. The use of a decision rule may facilitate the selection of the most desirable alternative, sorting of alternatives into classes arranged into a priority order, and ranking of alternatives from best to worst. This assessment of the alternatives is expressed by one score, the overall appraisal score. That is the value of a function that aggregates the outcomes of a decision alternative over all evaluation criteria with the user's preferences.

According to the *Weighted Linear Combination* decision rule a final appraisal score $e_i$ for each alternative i is computed by multiplying the jth criterion importance weight $w_j$ by the normalized outcome score of alternative i on criterion j [R6]. The assumption for using this decision rule is that evaluation criteria are preferentially independent (the importance attached to one criterion is independent from the importance attached to other criteria). For m alternatives and n criteria the appraisal score $e_i$ is computed using the following equation:

$$e_i = \sum_{j=1}^{n} w_j \cdot r_{ij}, \quad i = 1, \ldots, m$$

The *ideal point decision rule* calculates the final appraisal score for each alternative based on the separation of combined alternative outcomes from the ideal point [R6]. The ideal point represents a hypothetical alternative that comprises the most desirable outcomes for the evaluation criteria. The nadir represents a hypothetical alternative that comprises the least desirable outcomes for evaluation criteria. The alternative that is closest to the ideal point, and at the same time farthest from its nadir, is the best alternative under this decision rule.

The decision rule can be computed with the following procedure:

1. Calculate standardized criterion scores using the linear standardization formula:

$$X_{ij}^{'} = \frac{X_{ij}}{X_j^{\max}}$$

2. Calculate weighted standardized criterion scores.

$$V_{ig} = W_j \bullet X'_{i,j}$$

3. Identify positive-ideal and negative-nadir solutions.

$$A^* \rightarrow \text{ideal}$$

$$A^* = \{v_1^*, v_2^*, ..., v_j^*, ..., v_n^*\}$$

$$A^* = \{(\max v_{ij} | j \in J_1), (\min v_{ij} | j \in J_2) | i = 1, \dots, m\}$$

$J_1$: set of benefit criteria

$J_2$: set of cost criteria

$$A^- = \text{nadir}$$

$$A^- = \{v_1^-, v_2^-, ..., v_j^-, ..., v_n^-\}$$

$$A^- = \{(\min v_{ij} | j \in J_1), (\max v_{ij} | j \in J_2) | i = 1, \dots, m\}$$

4. Calculate separation measures from ideal – S* and nadir – S–.

$$S^* = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^*)^2}, \quad i = 1, ..., m$$

$$S^- = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^-)^2}, \quad i = 1, ..., m$$

5. Calculate the index of similarities to ideal.

$$C_i^* = \frac{S_i^-}{S_i^* + S_i^-}, \quad i = 1, ..., m$$

$$0 \le C_i^* \le 1$$

$$C_i^* = 0, \quad when \quad A_i = A^-$$

$$C_i^* = 1, \quad when \quad A_i = A^*$$

6. Create preference order of decision options, choose an option with the maximum $C_i^*$ or rank the options according to $C_i^*$ in the descending order.

Ideal point decision method relies on the notion of the best possible set of criterion scores as influenced by three aspects: (1) the ideal, (2) its nadir (i.e., worst combination of criterion scores), and (3) the distances from each option to the ideal and the nadir. Ideal point decision rule provides complete, interval scale ranking of decision alternatives. This means that the relative distance of each alternative to the ideal point can be computed. This decision rule avoids the restrictive assumption of independence among the evaluation criteria—made by additive and value/utility function-based decision rules. This makes the ideal point decision rule an attractive approach to decision problems in which the independence among criteria is difficult to test.

## 3.6 MCE module (an example)

This section is an example of the implementation of MCE in the BRIDGE DSS. This example is referred in order to make out the various BRIDGE DSS components.

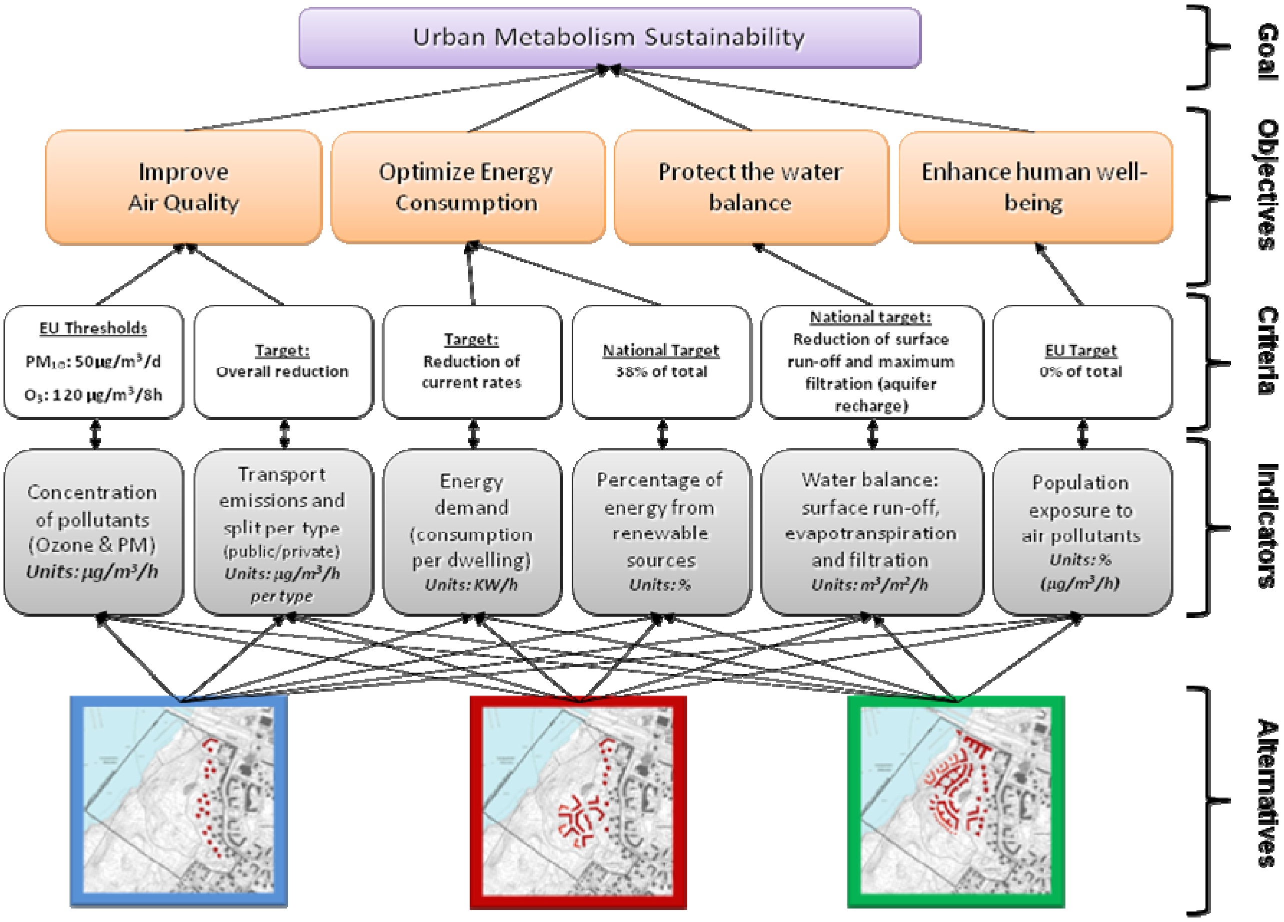


**Figure 6.** Goal, Objectives, Criteria and Indicators Hierarchy to be used in BRIDGE DSS (an example)

Figure 6 shows an example of hierarchy, similar to the one that will be used in BRIDGE DSS. The main goal of BRIDGE DSS is to ensure urban metabolism sustainability (top of hierarchy). The alternatives presented at the bottom of the hierarchy are an example of three land use alternatives for the Helsinki case study. Objectives anticipated to be met for Helsinki are for example: to improve the air quality, to optimize the energy consumption, to protect the water balance and to enchase the human well-being. Indicators are below the objectives in the hierarchy. For example, to ensure the improvement of air quality, indicators like concentration of pollutants and the transport emission and splitter types need to be calculated for each one of the alternatives. Criteria refer to legislation or guidelines to establish the indicators. Wherever specific thresholds or targets are not available, textual criteria are used. Hierarchy shown in Figure 6 is just an example. The complete set of objectives criteria and indicators to be used in BRIDGE DSS will be Deliverable D.5.1 – (Socio-economic and environmental workshops report).

The decision maker will be asked to define the relative importance of the objectives. This is done by completing matrices like the one shown in Table 3.The weight will be defined using the pair-wise comparison method described in Section 3.4:

**Table 3.** Objectives pair-wise comparison matrix example

| | **Air Quality** | **Energy Consumption** | **Water balance** | **Human-well being** |
|---|---|---|---|---|
| **Air Quality** | **1** | **$a_{12}$** | **$a_{13}$** | **$a_{14}$** |
| **Energy Consumption** | **$1/ a_{12}$** | **1** | **$a_{23}$** | **$a_{24}$** |
| **Water balance** | **$1/ a_{13}$** | **$1/ a_{23}$** | **1** | **$a_{34}$** |
| **Human-well being** | **$1/ a_{14}$** | **$1/ a_{24}$** | **$1/ a_{34}$** | **1** |

The values to be defined by the user are $a_{12}$, $a_{13}$, $a_{14}$, $a_{23}$, $a_{24}$ and $a_{34}$ (orange cells) of Table 1. The users will be asked to reply to question like:

“What is more important for this decision? Air Quality or Energy Consumption?” The reply will be a number derived from Table 2. One possible answer to this question for example would be that “Air Quality is weakly more important than Energy Consumption” and the value assigned to $a_{12}$ would be 3.

An example table may be the following:

$$A = \begin{bmatrix} 1 & 3 & 2 & 4 \\ 1/3 & 1 & 5 & 1 \\ 1/2 & 1/5 & 1 & 9 \\ 1/4 & 1 & 1/9 & 1 \end{bmatrix}$$

The weight vector according to the pair-wise comparison, described in Section 3.4, would be:

$$w = \begin{bmatrix} 0.3925 \\ 0.2589 \\ 0.2504 \\ 0.0982 \end{bmatrix}$$

Air quality weight is 0.3925, Energy Consumption weight is 0.2589, Water Balance weight is 0.2504 and Human well-being is 0.0982.

The same procedure is followed to assign weight to each indicator. A 2×2 matrix would be filled in for Air Quality indicators (see Figure 6), as is shown in Table 4.

**Table 4.** Indicators pair-wise comparison matrix example

| | **Concentration of pollutants** | **Transport Emissions** |
|---|---|---|
| **Concentration of pollutants** | **1** | **$a_{12}$** |
| **Transport Emissions** | **$1/ a_{12}$** | **1** |

Assuming that the weights have been assigned to the objectives and the indicators of Figure 6, the decision rule (Section 3.5) is being used in order to achieve a final appraisal score for the alternatives. An example illustrating the Weighted Linear Combination decision rule follows to retrieve a final appraisal score. Sample numbers of weights (Table 5) and indicator values (Table 6) are used to make the example clear.

**Table 5.** Sample weights computed using pair-wise comparison

| | Objectives weights | | Indicator weights |
|---|---|---|---|
| **Air Quality** | **0.3925** | **Concentration of pollutants** | **0.3333** |
| | | **Transport emissions and split per type** | **0.6667** |
| **Energy Consumption** | **0.2589** | **Energy demand** | **0.7500** |
| | | **Percentage of energy from renewable sources** | **0.2500** |
| **Water balance** | **0.2504** | **Water balance: surface run-off, evapotranspiration and filtration** | **1.0000** |
| **Human-well being** | **0.0982** | **Population exposure to air pollutants** | **1.0000** |

**Table 6.** Sample Indicator Values

| | Alternative 1 | Alternative 2 | Alternative 3 |
|---|---|---|---|
| **Concentration of pollutants** | **1.3587** | **0.3333** | **0.3333** |
| **Transport emissions and split per type** | **0.8796** | **0.6667** | **0.6667** |
| **Energy demand** | **2.1573** | **0.75** | **0.75** |
| **Percentage of energy from renewable sources** | **5.3268** | **0.25** | **0.25** |
| **Water balance: surface run-off, evapotranspiration and filtration** | **0.9874** | **1** | **1** |
| **Population exposure to air pollutants** | **1.0000** | **1** | **1** |

The final appraisal score for one alternative is computed by multiplying each indicator value by the respective weight, then sum the results for every objective, multiply each result by the corresponding objective weight and finally sum all results. For example, the final appraisal score for Alternative 1 is computed as

$$\begin{aligned} F_{Alt1} = & \left[ (1.3587 \times 0.3333) + (0.8796 \times 0.6667) \right] \times 0.3925 \\ & + \left[ (2.1573 \times 0.75) + (5.3268 \times 0.25) \right] \times 0.2589 \\ & + (0.9874 \times 1.0000) \times 0.2504 \\ & + (2.4654 \times 1.0000) \times 0.0982 \end{aligned}$$

where each line represents one objective.

The final score for each alternative is shown in Table 7. A radar diagram can be produced in order to give the decision maker more information about the importance of the objectives. Figure 7 shows the radar diagram produced by this example. Alternative 3 has the greater final score and it is considered the best decision according to this example data.

**Table 7.** Final Appraisal scores computed using Weighted Linear Combination decision rule

| | **Final Appraisal Score** |
|---|---|
| **Alternative 1** | **0.443507** |
| **Alternative 2** | **0.308393** |
| **Alternative 3** | **0.457766** |

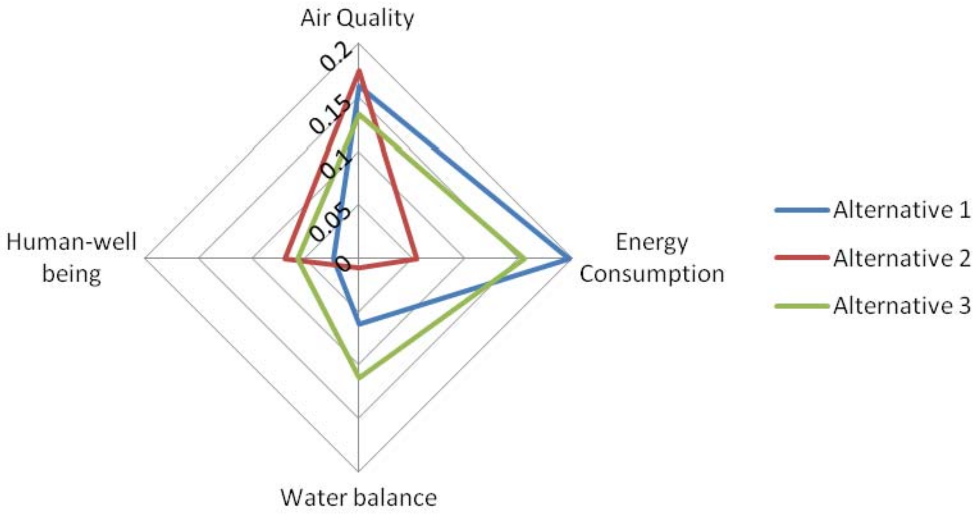


**Figure 7.** Radar diagram representing the results of the Weighted Linear Combination decision rule.

## 3.7 The role of Cellular Automata

The (Cellular Automata) CA module to be incorporated into the BRIDGE DSS for the simulation of land use dynamics is an adaptation, with some modifications, of the well known Constrained Cellular Automata approach (CCA) [R19],[R18], [R19]. In particular, the CA module has been designed in order to satisfy different objectives, namely: *(i)* the ability to operate at a reasonably high spatial resolution; *(ii)* the inclusion of an adequate simulation of the spatial processes that determine the land use patterns; *(iii)* the capability of processing a suitable representation of relevant landscape features and legal constraints on land use.

The model enables to incorporate the dynamics caused by large-scale processes (e.g. the demography or the development of specific economic sectors) through the linkage of more traditional dynamic models (i.e. a-spatial demographic, economic and environmental models) or even through the use of simple trends (e.g. extrapolations based on historical data or representing scenarios of development) [R18]. In other words, the allocation of the land use may depend both on an aggregate model (or trend) exogenous to the CA, and on the local CA-based interactions (i.e. on the basis of the local transition rules and of the cell characteristics). In this sense, the CCA can be viewed as a way to determine the spatial distribution of an aggregate land-use demand, taking into account for the local interaction between different land-uses as well as the physical, environmental and institutional factors and other relevant characteristics characterizing each cell. Thus, the CCA model can easily account for the planning decisions whose broader effects in terms of a spatial distribution of land-uses have to be evaluated.

In the CCA model each cell has a set of properties representing all relevant physical, environmental, social and economical characteristics, as well as cell's accessibility depending on the transportation network, and the imposed legislative constraints (i.e. the zoning status for each land-use). This allows the model to be linked both conceptually and practically with GIS [R18], [R16], [R17] and indeed the cell space on which the CA operates can be easily obtained from the layers of a raster GIS.

The cellular space consists of a rectangular grid of square cells were, likely, each cell will represent an area ranging from 50 m to 200m square, depending on the particular case study. The grid size and shape will also vary according to the map of the city being modelled (e.g. typical applications for European cities were made using 500 by 500 cells). Each cell is characterised by:

- a *suitability factor* for each land use involved in dynamics. The suitabilities are values in the interval [0, 1] representing the "propensity" of a cell to support a particular activity or land use (e.g. can be computed as a normalized weighted sum or product of relevant physical, environmental and institutional factors characterising each cell). The suitabilities can be either pre-calculated in a GIS, and in this case remain constant during the simulation, or dynamically computed by the CCA model itself during the simulation.
- an *accessibility factor* for each land use, reflecting the importance of access to the transportation networks for the various land uses or activities (e.g. commerce require better accessibility than residential use). Again, these quantities can be either pre-calculated in a GIS, starting from a vector representation of the transportation network, or can be computed by the CCA model itself before starting the simulation.
- its *zoning status* in terms of an exclusion flag every land use;
- its *current land use/function*. In general, the model includes both static land uses (i.e. not changing during the simulation but influencing the dynamics in the cell neighbourhood in terms of attractive or repulsive effect) and dynamic land uses. The specific land uses included in the model will likely depend on the particular case study and namely on the availability of spatial data. Broadly speaking, static land uses will include: road and rail networks, subways, airports, vegetated areas, water bodies, agricultural areas, forests etc. The actively modelled land uses will likely include: residential (if possible partitioned in dense, medium dense, continuous and discontinuous sparse), industrial areas; commercial areas; public and private services; port areas; urban abandoned land. As mentioned before, the dynamic land uses are forced by demands for land provided to the CCA.

As in every CA, each cell is characterized by a neighbourhood, namely the set of cells the state of which can influence the dynamic of the cell itself (i.e. the change of state of a cell at each time-step depends on the states of the cells within its neighbourhood). In the CCA model adopted in BRIDGE the neighbourhood is defined as the circular region around the cell with a typical radius that ranges from 0.5 Km to 1.5 Km depending on the grid resolution (i.e. it must be sufficient to allow local-scale spatial processes to be captured in the CA transition rules).

In the model, a neighbourhood effect representing the attraction (positive) and repulsion (negative) of the different land uses and land covers within the neighbourhood is defined. In particular, each cell in the neighbourhood contributes to the evolution of the central cell through the neighbourhood effect which is expressed as a parameter-dependent function of its distance from the neighbourhood centre (in general, cells that are more distant in the neighbourhood will produce a smaller effect). In addition, a positive attraction of a cell on itself (zero-distance effect) represents an inertia due to the costs of changing from one land use to another.

A vector of transition potentials (one potential for each actively modelled land use) is calculated for each cell on the basis of the suitability, accessibilities, zoning, and neighbourhood effects. Then, transition potentials determine on a step by step basis the overall dynamic of the system.

Since, as mentioned above, the transition function is of parameter-dependent type the model need a preliminary calibration phase that can be based on available historical spatial data concerning the area under study.

The typical output from the CCA model are maps showing the predicted evolution of land uses in the area of interest, over a predefined period of time (e.g. ten years). By varying the inputs into the CCA model (e.g. zoning status, transport networks, presence of facilities and services), the model can be used to explore the future urban development of the area under consideration under alternative spatial planning and policy scenarios.

### *Previous Application of CCA modules*

Besides the wide scientific literature, the reliability of the CCA approach is well proved by a successful application achieved by some EU research projects. For example, in the MODULUS project, aimed at the development of a DSS in the domains of land degradation and desertification in the coastal watersheds of the Northern Mediterranean, the CCA approach was exploited to build a land-use sub-model. In the latter model, the land claims resulting from demographic and economic changes are allocated in a grid of geo-referenced cells taking into account, among other characteristics, the suitability of each cell for each specific activity, the cell accessibility and regulations provided by planning decisions. Another well-known urban-CA application has been realised in the context of MOLAND (Monitoring Land Use / Cover Dynamics), a research project carried out at the Institute for Environment and Sustainability - Land Management and Natural Hazards Unit of the EU Joint Research Centre. MOLAND was devoted to support the preparation, definition and implementation of EU policies and legislation. In MOLAND, a CCA approach [R20], [R21], [R22] coupled with various other models was adopted to explore the consequences of spatial planning and policy decisions and to monitor where development in urban areas is likely to occur. For example, the application of the MOLAND urban growth model to Dublin is illustrated in Figure 8(more information can be found at http://moland.jrc.ec.europa.eu)

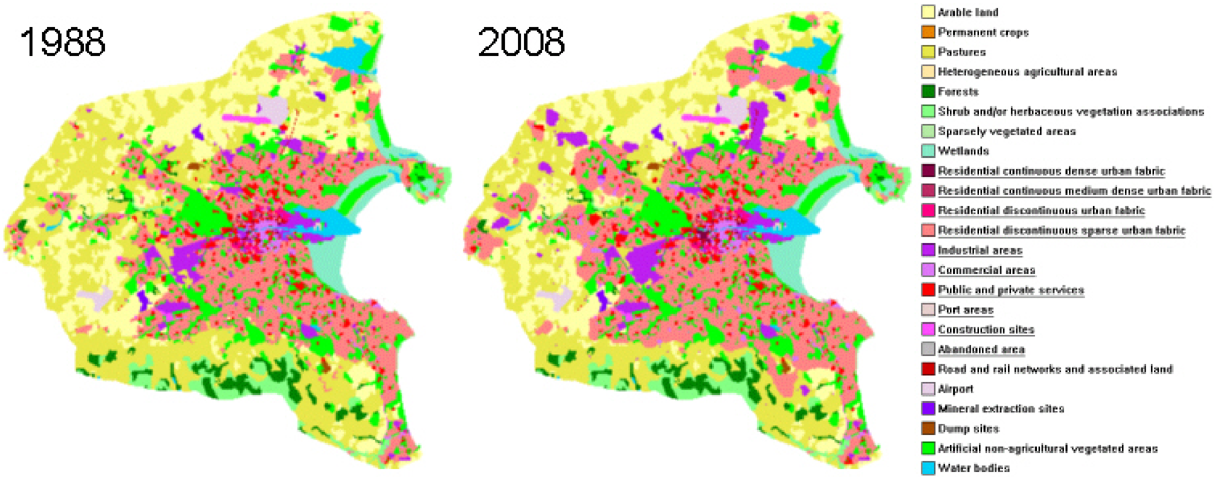


**Figure 8.** Modelling urban growth in Dublin through a CCA model: initial land use map (1988) and simulated land use map (2008) (from http://moland.jrc.ec.europa.eu)

# 4. System Architecture

## 4.1 Geographic Information System

The basis for geospatial decision support is the GIS technology. GIS plays a key role by contributing the spatial dimension since it is the repository of all data and interacts with the rest of the system like the numerical models. GIS is *a system for capturing, storing, checking, integrating, manipulating, analyzing and displaying data which are* ***spatially referenced*** *to the Earth geographic space,* according to the Association for Geographic Information [R10].

GIS technology integrates common database operations such as query and statistical analysis with the unique visualization and geographic analysis benefits offered by maps. These abilities distinguish GIS from other information systems and make it valuable to a wide range of public and private enterprises for explaining events, predicting outcomes, and planning strategies.

A GIS stores information about the earth as a collection of thematic layers/coverage linked together by geography. This simple but extremely powerful and versatile concept has proven invaluable for solving many real-world problems from environmental impact assessment, to recording details of planning applications, to modeling global atmospheric circulation.

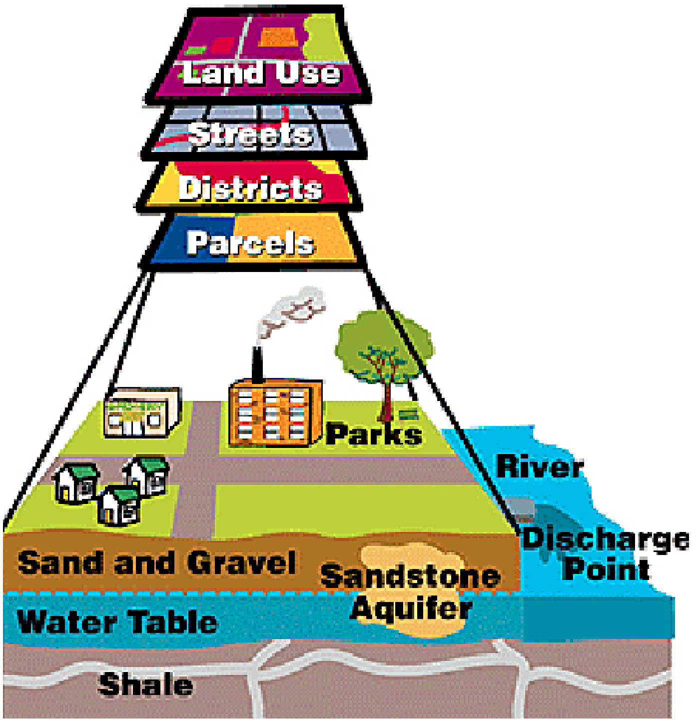


**Figure 9.** GIS Thematic Layers

As shown in Figure 9 [R11], each thematic layer or coverage represents some spatial information such as altitude/elevation at every point, the boundaries of a city, population density, land use, streets etc. There is no limitation on the number of layers that a GIS project can have. The amount of layers depends on the information needed to address all components of a problem.

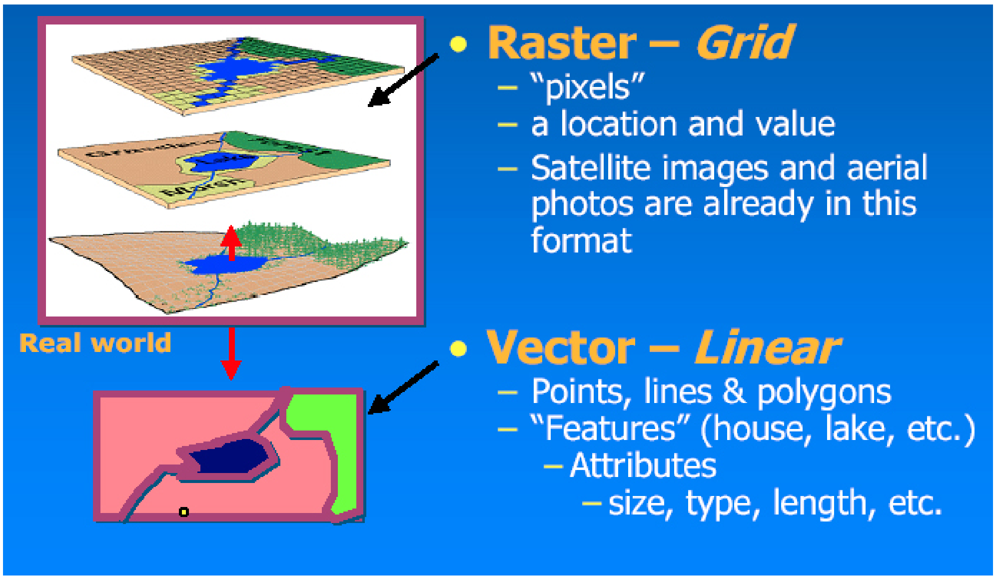
The various thematic layers are “interrelated” because they contain a geographic/ spatial reference. The geographic reference can be explicit (such as the longitude and latitude or a national grid coordinate), or implicit (such as an address, postal code, census tract name, or road name). The only true geographic coordinates are the longitude and latitude of a spatial reference system. GIS draws its power from this common geographic referencing system. Existing information can be combined to derive new, more complex information. Spatial analysis tools allow spatially-specific answers for questions such as: “how far away are the population centers from a pollutant site?”, or “what are the soil characteristics near the stream?”.

## 4.2 Types of data in a GIS

### ***Spatial data - geographic***

*Vector*

Geographic information systems work with two fundamentally different types of geographic –data storage: the "vector" and the "raster" representation as shown in Figure 10 [R11]. In the vector representation, information about points, lines, and polygons is encoded and stored as a collection of *x,y,z* coordinates. The location of a point feature, such as a the location of a store, can be described by a single *x,y,z* coordinate. Linear features, such as roads and rivers, can be stored as a collection of linked point coordinates that is a line, more commonly referred to as polylines. Polygonal features, such as river catchments, land use types can be stored as a closed loop of coordinates.



- **Raster – *Grid***
  - “pixels”
  - a location and value
  - Satellite images and aerial photos are already in this format
- **Vector – *Linear***
  - Points, lines & polygons
  - “Features” (house, lake, etc.)
    - Attributes
      - size, type, length, etc.

**Figure 10.** GIS Spatial data

*Raster data*

The vector model is extremely useful for describing discrete features, but less useful for describing continuously varying features such as pollution levels, soil type, slope degrees or elevation. The raster representation has evolved to model such continuous features. A raster image divides the entire study area into a regular grid of cells. Each cell contains a single value which can correspond to the elevation, the land use etc. The raster model is therefore a collection of grid cells rather like a scanned map or picture. However, unlike pictures, associated with every cell there is a value which can be the third dimension (such as elevation). Both the vector and raster models have unique advantages and disadvantages. Modern GISs are able to handle both models.

***Spatial data – attributes***

Associated with each geographic entity (whether point, line, polygon or raster cell) there can be a set of alphanumeric attributes (e.g. descriptions, measurements or classifications) that describe the entity. Attributes are assumed to be identical for the whole geographic feature to which they correspond.

Attributes can be descriptive/qualitative or quantitative. The former describe the entity while the latter associate a numeric value with the entity. Typical examples of attributes are:

- Descriptive/qualitative
  - Land cover/use type
  - Zoning area type
  - Buildings outlines
- Quantitative
  - Population of an area
  - Outflow from a source
  - Traffic size
  - Elevation

## 4.3 Required functionality of the GIS in BRIDGE

The BRIDGE DSS will be developed in a GIS environment: (1) development of the database, (2) performing the analysis and (3) reporting the results.

The BRIDGE database will contain all BRIDGE related data (GIS data and model outputs data) which should be seamlessly integrated in the complete system. The development of the BRIDGE database includes four operations: (a) Assembling the data, (b) Preparing the data for analysis, (c) organize and store the data and (4) feed the data to the models and integrate the results of the models to the database. The results of the input data analysis will produce a series of output data that will be used to produce the reports (maps (visualization), changes in the various indicators for the different alternatives and final scores)

The analysis will also be performed in GIS environment and is indispensable component of the complete system. Analysis operations can be broadly differentiated into three major groups

- GIS analytical capabilities
- Database connectivity requirements
- System requirements

The first category includes the various spatial operations performed in GIS, while the second includes requirements imposed by the database system. The system requirements emanate from the structure of the proposed system and have been described in Chapter 3 – Conceptual Design. The requirements for each one of these categories are explained in the following sections.

### 4.3.1 GIS analytical capabilities

Large and complex datasets such as those needed in BRIDGE require extensive GIS functionality. The GIS subsystem should have the capabilities for:

*Raster data manipulation*
Several of the datasets to be used in BRIDGE will be of the raster type and therefore this is a very important characteristic that the GIS system should possess. Typical examples of such datasets include: the land cover/land use maps, the elevation information maps (DTMs) and the output of the models.

*Vector data manipulation*
The road network, the railway network, the concentration of population, the buildings etc. will be represented by poly-lines and polygons. Therefore, there is a requirement that the GIS system can manipulate vector datasets as well.

*Map overlays*
This is the capability to create overlays of two or more layers to contrast and correlate information areas.

*Buffer generation*
With the buffer capability the GIS can generate buffers around points, lines, or polygons to identify all features within the buffer area. The GIS can then produce a tabular report listing all of the identified features.

*Digital terrain model (DTM) creation and analysis*
In a GIS a topographic map (a map displaying elevations), can be manipulated/analysed in three different but equivalent methods. The first is a pure raster model coverage where for each cell there is the associated elevation. The second is a DTM that permits a 3-D visualization of an area and the last one is through the use of Triangulated Integrated Networks (TIN) in which the different measurements are connected through a set of triangles. Although the term DTM is used most often it must be stressed that all three methods are equivalent and arrive at the same result. In BRIDGE, DTM manipulation could be a significant feature that the GIS should have. The need for DTM capability depends on the type of datasets available and the visualization required. If datasets are available that have information on the height of the building then DTM manipulation would be needed.

*Capability to convert between various coordinate systems*
In a GIS system the coordinate system used is either spherical or rectangular. The spherical coordinates are the longitude and latitude and are unique for a given Ellipsoid and Datum system. However, since paper maps and coverages in a GIS are 2-dimensional a projection system must be used for converting the spherical coordinates into a rectangular grid. There is not any unique projection system. UTM is a projection system often used, however, in almost all countries a local projection system is used. In BRIDGE, since the system will be used to store datasets from the different case studies it is expected that the local projection system will be used. Therefore, GIS must handle the various projection systems used in BRIDGE case studies.

*Boundary dissolve*
This is the ability to regroup and reclassify existing spatial entities to form new entities or coverage. An example here would be to reclassify the land use categories, to form a new set of land uses based on some common characteristic.

*Tabular data analyses*
Because GIS is based on a full-featured relational database, it can generate reports of tabular data from the database.

### 4.3.2 Database connectivity requirements

In a GIS project the spatial entities are stored in the system, however, the various attributes associated with each spatial object are stored in a database management system (DBMS). The data structures are of the relational type; hence, there is a requirement that the GIS should be able to operate transparently with the RDBMS system to be used.

This is not a major issue in a Microsoft Windows environment as standard ODBC drivers allow communication between GIS and any DBMS such as Oracle, SQL-server, Access etc.

Since BRIDGE will be operating in a Microsoft Windows environment, it should be expected that all modern GIS have this capability.

## 4.4 Models Implementation - Connectivity

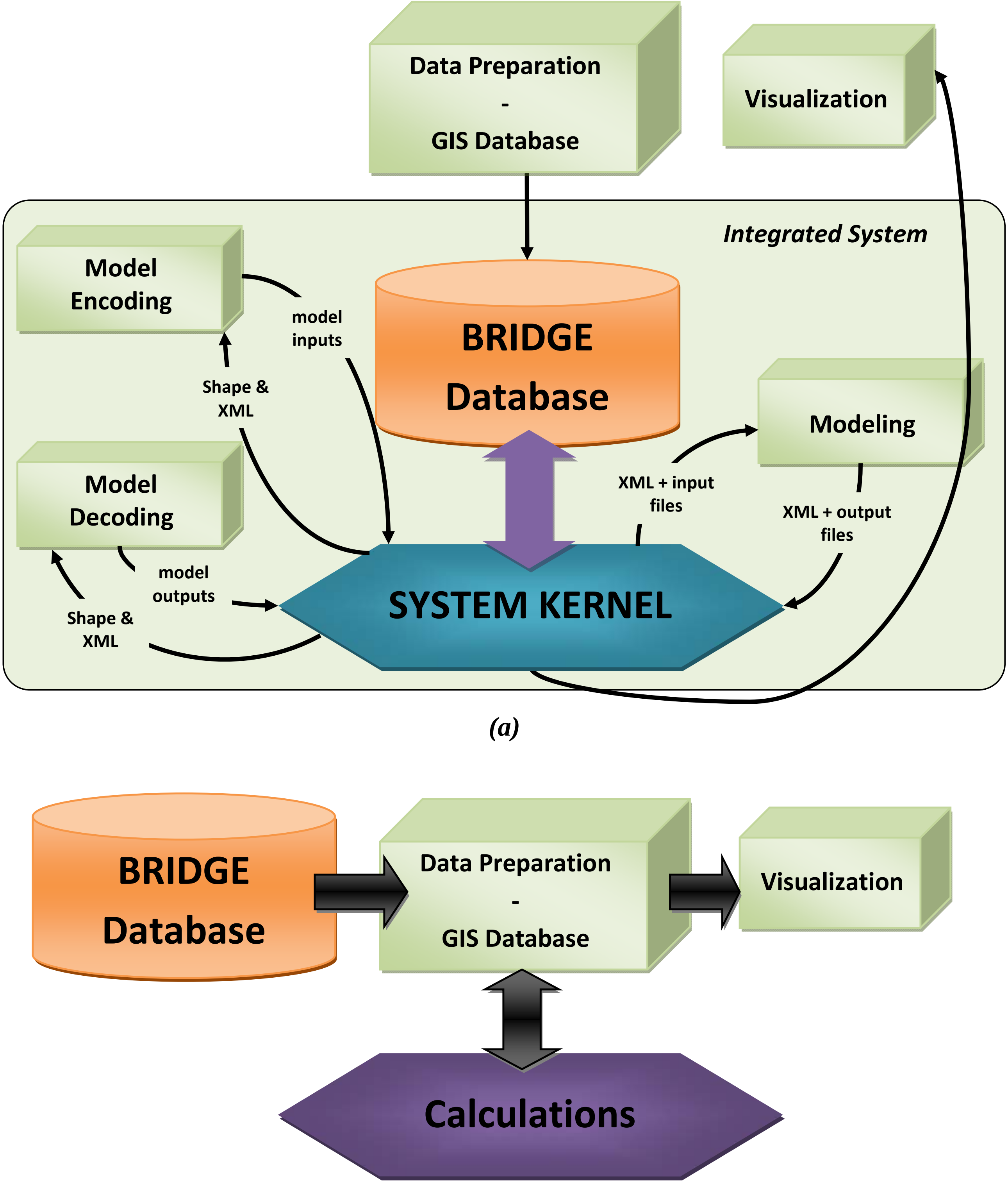
Combination of numerical models with a mapping and scheme editing will take place in BRIDGE. The indicators are estimated by various environmental models in or measures that take as inputs various parameters related to the location of resources and infrastructure, topography of the area etc. Consequently (based on a set of equations) they estimate the indicators in different parts of the city. The GIS takes the results of the model and permits map visualization of distribution and patterns at different areas throughout the city.

There are two different ways that the models and the GIS could interact.

A. <u>Completely integrated system - Generation of model input files from the GIS- Online system</u>

In this form the models are integrated in the GIS. As shown in Figure 11, all datasets are stored in the GIS and the *"model encoding"* (or pre-processor) component generates the necessary input files for the models. The models then run and produce output files. Output files are treated through a *"model decoder"* (post-processor) component and stored in the GIS databases and eventually visualized in the GIS.

The "model encoder", a key feature of this architecture, uses GIS functionality to prepare the input files needed for running the models. By including such a component, end users can immediately simulate the results of various "what if" scenarios without being concerned about input file format and other details related to the operation of the models. The "model decoder" operates on the output file of the models and can be considered to be a filter that reorganizes the output data in a format that is amenable to GIS manipulation and therefore for map preparation.



*(b)*

**Figure 11.** BRIDGE system architecture and data flow (a) for on-line models and (b) for off-line models.

In that case the following operations would be carried out in a transparent way (that is without user interference) in the BRIDGE system.

- “Model encoder” prepares the new input files taking into account the various GIS datasets and the new parameters;
- The model runs using the new input file and produces an output file with new results;
- “Model decoder” translates output file into GIS datasets, and
- GIS is used to prepare and display maps.

If a “model encoder” was not included end users would have to go and manually change the input files of the model before being able to execute the model. This implies that they would have to know exactly the input file formats etc. Additionally, if a “model decoder” was not part of the overall system the translation of output file to GIS datasets would have to be performed manually.

The rationale for this approach is that it permits end users to easily perform “what if” scenarios without being concerned about the models. However, this approach is valid **only** if the necessary input files for the model can be prepared by manipulating the various GIS datasets. So implementation of this procedure is a function of the model being used and the difficulty associated with preparing the input files.

An issue here is whether the model runs inside the GIS or is an outside component. The model being a separate executable (or DLL procedure) could run from inside the GIS system if there are no memory limitations, or the execution time does not take very long. If execution time takes a long time, it might be preferable that the model runs outside the GIS system.

B. Generation of model input files outside the GIS, GIS used for visualization of results only- Off-line system

In this form the generation of the input files for running the models is performed independently of the GIS. The results of the models are imported in the GIS through a “*model decoder*” component and the GIS is used to produce maps. There is no “model encoder” and the models and the GIS are “connected” through the output files of the models. This is a more simple architecture, but potentially more realistic one if the input files and the other parameters needed for running the models cannot be generated from inside the GIS, or the models are too complex to be integrated.

## 4.5 Implementation of on-line models (an example)

An example is presented in this section of the URBAIR urban air quality model. URBAIR is a second generation Gaussian plume model intended to be used for distances up to about 10 km from the source. More information on the model description can be found in D.4.1 Model Selection Report [R24].

The URBAIR model requires the following input data:

i. one model control file

ii. one main input file containing the simulation control parameters, source data and receptor data and

iii. two input meteorological data files

The encoder will create those data according to the model specifications:

i. The model control file makes use of a parameter call approach to specify the names of the input and the output data files:

```
----------------------------------------------
File to control URBAIR input-output data files
----------------------------------------------
input\Viseu_case_study.dat
output\UrbAir_output.dat
```

ii. The main input file (in the example, called Viseu_case_study.dat) includes the run control parameters, source parameter data, defines the receptor locations, specifies the location and parameters regarding the meteorological data, and specifies the output options:

```
CO START
   TITULO    CO_Atmospheric_dispersion_in_urban_environment
   POLUENTE  CO
   MEDIAS    1  24  period
CO FINISH

FT START
**          FtId     FtTipo    X        Y       Z
FT POSICAO  STACK1   POINT   -320.0    420.0    0.0
   POSICAO  STACK2   POINT   -310.0    360.0    0.0
   POSICAO  STACK3   POINT   -307.0    336.0    0.0
   POSICAO  STACK4   POINT   -300.0    320.0    0.0
...................................................
...................................................
   DISTANCY STACK223     -32.83  -22.28   -6.69   14.70   20.05   23.00
   DISTANCY STACK223      15.10   20.30   27.40   33.66   38.90   66.56
   DISTANCY STACK223      67.41   36.14   21.00    5.23  -10.71  -26.31
   DISTANCY STACK223      32.83   22.28    6.69  -14.70  -20.05  -23.00

   EMISSOES  input\emissoes.dat  ALL
   FTAGRUPA  ALL
FT FINISH

RE START
RE MALHA    rede2 TIPO
                 XYINC  -2000.  20    200. -2000.  20    200.
RE MALHA    rede2 END
RE FINISH

ME START
   SPRFFILE  input\meteo_superficie.dat
   PERFFILE  input\meteo_perfis.dat
   SPRFDATA  10002  2006  Viseu
   PERFDATA  10001  2006  Viseu
ME FINISH

OU START
   TABELAS   1    all  result   output\CO_conc_1h_mesh.dat
OU FINISH
```

iii. The two input meteorological data files will also be created by the encoder:

```
    41.3N    74.00W          Radio: 00010001  Super:    10002
6 6 20 171  1   -999    -9     -9    -9  -999 -999  -99999 0.12 2    1   0
6 6 20 171  2   -0.7 0.025     -9    -9  -999    9       2 0.12 2    1 0.5
6 6 20 171  3   -0.7 0.025     -9    -9  -999    9       2 0.12 2    1 0.5
6 6 20 171  4   -0.7 0.025     -9    -9  -999    9       2 0.12 2    1 0.5
6 6 20 171  5   -0.7 0.025     -9    -9  -999    9       2 0.12 2 0.71 0.5
6 6 20 171  6    4.1 0.114  0.061 0.008     2   89   -32.2 0.12 2 0.36   1
6 6 20 171  7   89.2 0.256  0.476 0.008    43  297   -16.7 0.12 2 0.22 2.1
6 6 20 171  8  173.7 0.363  0.845 0.008   124  503   -24.5 0.12 2 0.17 3.1
6 6 20 171  9  249.1 0.281  1.192 0.008   242  345    -7.9 0.12 2 0.16 2.1
6 6 20 171 10  308.4 0.228  1.499 0.008   390  252    -3.4 0.12 2 0.15 1.5
6 6 20 171 11  349.1 0.119   1.76 0.008   558   99      -1 0.12 2 0.15 0.5
6 6 20 171 12  355.9 0.338  1.937 0.008   730  452    -9.7 0.12 2 0.15 2.6
6 6 20 171 13  354.7 0.384  2.074 0.008   899  546   -14.2 0.12 2 0.15 3.1
6 6 20 171 14  336.4 0.382  2.157 0.008  1065  543   -14.8 0.12 2 0.15 3.1
6 6 20 171 15    298 0.424   2.16 0.008  1208  635   -22.8 0.12 2 0.15 3.6
6 6 20 171 16  241.9 0.451   1.46 0.008   778  696   -57.2 0.12 2 0.16 4.1
6 6 20 171 17  172.5 0.502  1.891 0.008  1399  817   -65.3 0.12 2 0.18 4.6
6 6 20 171 18   89.3 0.489  1.532 0.008  1436  787  -116.7 0.12 2 0.23 4.6
6 6 20 171 19    3.7 0.419  0.531 0.008  1425  627 -1748.2 0.12 2 0.38 4.1
6 6 20 171 20  -36.6 0.339     -9    -9  -999  457    94.9 0.12 2    1 3.6
6 6 20 171 21  -24.1 0.222     -9    -9  -999  248    40.7 0.12 2    1 2.6
6 6 20 171 22  -24.2 0.222     -9    -9  -999  241    40.3 0.12 2    1 2.6
6 6 20 171 23   -2.9 0.051     -9    -9  -999   73     4.1 0.12 2    1   1
6 6 20 171 24   -999    -9     -9    -9  -999 -999  -99999 0.12 2    1   0
6 6 21 172  1   -2.9 0.051     -9    -9  -999   26       4 0.12 2    1   1
6 6 21 172  2   -6.6 0.076     -9    -9  -999   49     6.1 0.12 2    1 1.5
6 6 21 172  3   -9.5 0.051     -9    -9  -999   26       4 0.12 2    1   1
6 6 21 172  4   -6.6 0.076     -9    -9  -999   49     6.1 0.12 2    1 1.5
6 6 21 172  5   -2.9 0.051     -9    -9  -999   26     4.1 0.12 2 0.72   1
6 6 21 172  6    5.2    -9     -9    -9     3 -999  -99999 0.12 2 0.36   0
6 6 21 172  7   91.6 0.201  0.538 0.008    61  207    -7.9 0.12 2 0.22 1.5
6 6 21 172  8  176.4 0.215  0.946 0.008   172  229      -5 0.12 2 0.17 1.5
6 6 21 172  9    251 0.113  1.325 0.008   333   91      -1 0.12 2 0.16 0.5
6 6 21 172 10  309.8 0.228  1.661 0.008   531  251    -3.4 0.12 2 0.15 1.5
6 6 21 172 11  350.3  0.29  1.947 0.008   757  359    -6.2 0.12 2 0.15 2.1
6 6 21 172 21   -6.5 0.076     -9    -9  -999   63     6.1 0.12 2    1 1.5
6 6 21 172 22   -6.5 0.076     -9    -9  -999   49     6.1 0.12 2    1 1.5
6 6 21 172 24   -6.5 0.076     -9    -9  -999   49     6.1 0.12 2    1 1.5
```

The results of the model will be saved in a txt file (in the example, called CO_conc_1h_mesh.dat)

```
        X              Y         AVERAGE CONC     DATE        AVE
 _____________  _____________  _____________  __________  _______
 -2000.00000    -2000.00000       0.00000      06062001     1-HR
 -1800.00000    -2000.00000       0.00000      06062001     1-HR
 -1600.00000    -2000.00000       0.00000      06062001     1-HR
 -1400.00000    -2000.00000       0.00000      06062001     1-HR
 -1200.00000    -2000.00000       0.00000      06062001     1-HR
 -1000.00000    -2000.00000       0.00000      06062001     1-HR
  -800.00000    -2000.00000       0.00000      06062001     1-HR
  -600.00000    -2000.00000       0.00000      06062001     1-HR
  -400.00000    -2000.00000       0.00000      06062001     1-HR
  -200.00000    -2000.00000       0.00000      06062001     1-HR
     0.00000    -2000.00000       0.00000      06062001     1-HR
   200.00000    -2000.00000       0.00000      06062001     1-HR
   400.00000    -2000.00000       0.00000      06062001     1-HR
   600.00000    -2000.00000       0.00000      06062001     1-HR
```

This file contains the spatial location (X,Y) of each receptor, pollutant concentration (AVERAGE CONC) and correspondent time period (DATE) within the simulation period. To identify the calculation period, an additional column is also defined (AVE).

The decoder reads the abovementioned file and updates the system database.

## 4.6 Coupling the CCA module and GIS

The integration of CA simulation engines into existing GIS systems has been proposed elsewhere (e.g. loose coupling based on the Remote Procedure Call paradigm or other proprietary protocols, using of scripting languages, development of plug-ins etc.). However, the coupling of simulation engines with proprietary GIS can hardly provide the necessary modelling flexibility and a satisfactory computational efficiency. Thus, at present for CA model based on complex transition functions, a practical approach is to couple GIS to special purpose CA software module. This is the approach that will be taken in BRIDGE. In particular, the CA module will be based on the MAGI C++ library [R23], which has some important characteristics for the present application: (i) it is computationally efficient; (ii) it is based on a general CA meta-model which permits the effective implementation of complex CA models; (iii) it is able to directly access some common raster and vector GIS data format. In particular, a pre-processor component integrated in the GIS will produce the necessary input data starting from the required GIS layers. Then, the CCA module will execute the simulation producing output files consisting of maps and synthetic statistics of the results. Finally, through a post-processor component, the CCA model outcomes can be incorporated into the GIS database for the DSS purposes.

According to the CCA model outlined above, the GIS pre-processor module should provide (in the simpler case in which suitability and accessibilities are static and pre-computed before the simulations) to the CCA module raster maps representing the suitability, the accessibility, zoning status and initial land uses. In addition, the CCA module requires the set of parameters previously determined for the specific case study through the calibration phase.

## 4.7 Recommendation on which GIS to integrate

The criteria used to select the GIS to integrate within the BRIDGE system were the following:

- Satisfaction of requirements outlined in the previous chapter (e.g. versatility of formats and tools);
- Potential acceptance in the marketplace of the BRIDGE system;
- Familiarity of the pilot users with the chosen software;
- Interoperability with other GIS applications of the users'; and,
- Future expansion of the system.

There are several GIS software packages, commercial or open source. The BRIDGE DSS will be built on the ArcGIS software from ESRI, Inc. as it satisfies the criteria above and provides the versatility and tools needed to achieve the project's objectives with regards to the DSS.

ArcGIS is a family of software products that form a complete GIS built on industry standards that provide exceptional, yet easy to use, capabilities right out of the box. ArcGIS is a complete, single, integrated system for geographic data creation, management, integration, and analysis. Much more than a specialized offering for a small niche of GIS specialists, ArcGIS is designed as a scalable system that can be deployed in every organization, from an individual desktop to a globally distributed network of people. The product family includes desktop products (ArcView, ArcEditor, ArcInfo), server products (ArcSDE) and web products (ArcIMS) for serving applications.

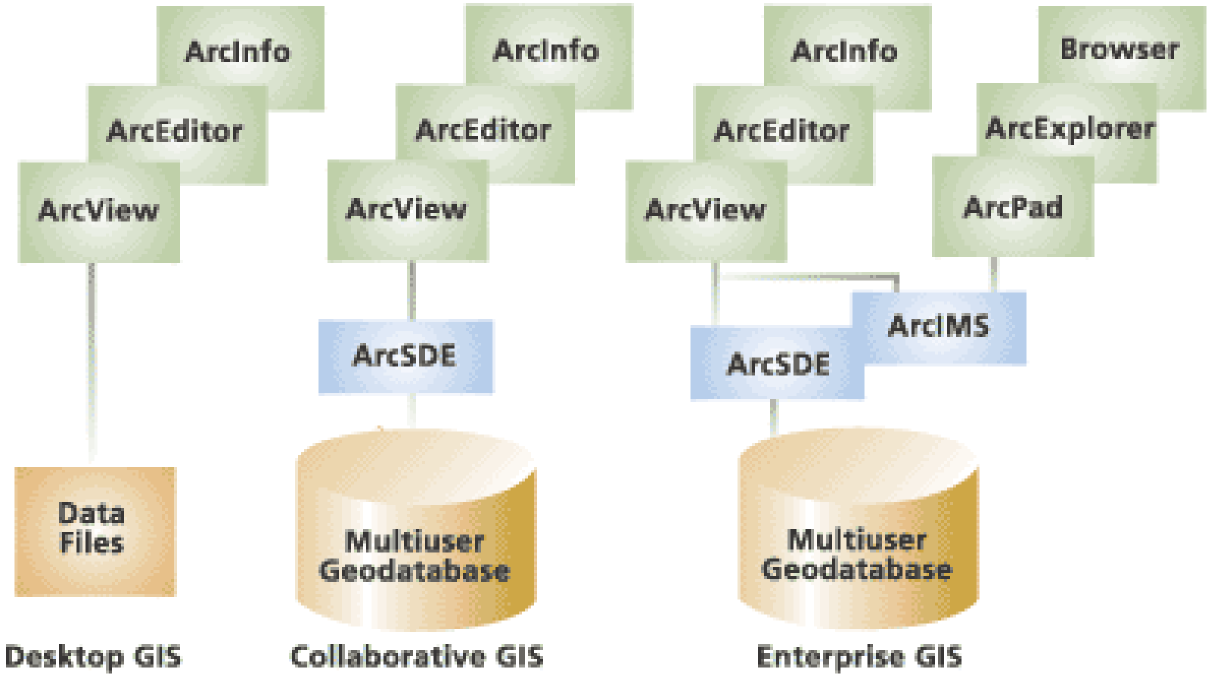


**Figure 12.** ArcGIS scalable.

## 4.8 Datasets to be included

- Vector datasets (topological and topographic)
- Attribute datasets
- Raster datasets

**Vector Datasets**

Vector data is essential to identify the geographical location of objects and features to be included in the modeling assessment to produce maps. These data must be 'captured' digitally as either points, lines or polygons. Vector data can be created by digitizing existing paper maps or from aerial or satellite photography, and could include:

- Area Topography
    - Roads (centerlines and/or double lines)
    - Building outlines
    - Land cover/ land use.
- Boundaries of statistical areas with information on population
- Digital Terrain Models (DTM's), which come in either grid points with heights or as interpolated contour lines. Some models import DTM data as either points or as contour lines.

**Attribute Data**

The Attribute data required in general is as follows:

- Road characteristics
    - Road surface
    - Slope
    - Others

- Buildings characteristics
    - Height,
    - Material used for façade (glass, bricks etc.)

- Statistical areas
    - Population,
    - Other socioeconomic characteristics of the population

A complete list of the datasets that will be included in the BRIDGE DSS Database can be found in Deliverables D.3.1, D.3.2 and D.3.3 [R25],[R26],[R27]. Example of three case studies is shown in Figure 13.

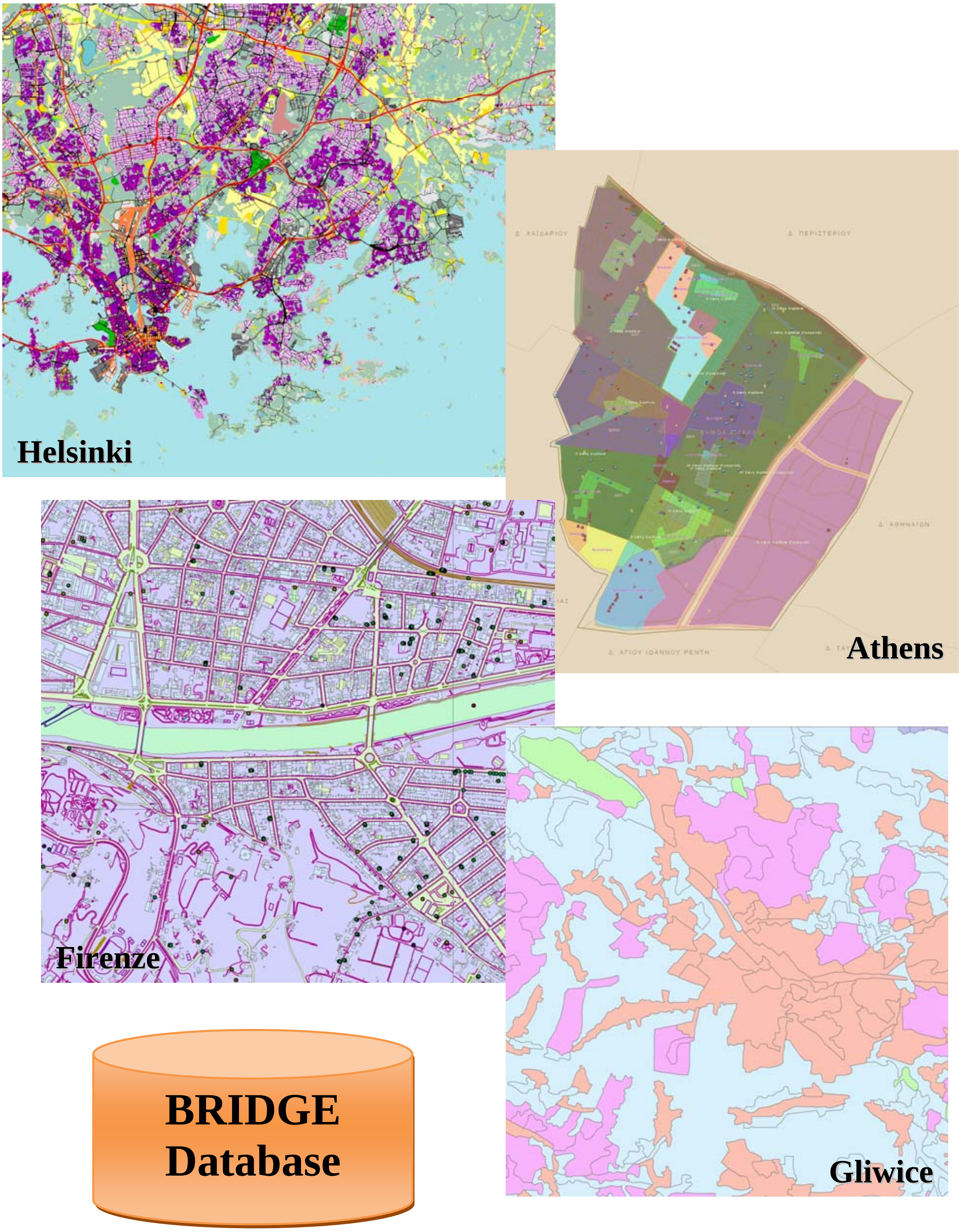


**Figure 13.** BRIDGE Database