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Article

Incorporating Bio-Physical Sciences into a Decision Support Tool for Sustainable Urban Planning

Zina Mitraka [1,*], Emmanouil Diamantakis [1], Nektarios Chrysoulakis [1], Eduardo Anselmo Castro [2], Roberto San Jose [3], Ainhoa Gonzalez [4] and Ivan Blecic [5]

1. Foundation for Research and Technology—Hellas, Institute of Applied and Computational Mathematics, N. Plastira 100, Vassilika Vouton, P.O. Box 1385, GR-71110 Heraklion, Greece; E-Mails: diamanda@iacm.forth.gr (E.D.); zedd2@iacm.forth.gr (N.C.)
2. Research Centre on Governance, Competitiveness and Public Policies (GOVCOPP) and Department of Social, Political and Territorial Sciences, University of Aveiro, 3810-193 Aveiro, Portugal; E-Mail: ecastro@ua.pt
3. Environmental Software and Modelling Group, Computer Science School, Technical University of Madrid, Campus de Montegancedo, Boadilla del Monte 28660 Madrid, Spain; E-Mail: roberto@fi.upm.es
4. Centre for the Environment, School of Natural Sciences, Trinity College Dublin, Dublin 2, Ireland; E-Mail: agonzal@tcd.ie
5. Department of Architecture, Design and Planning, University of Sassari, Centro Euro-Mediterraneo per i Cambiamenti Climatici, Piazza Duomo 6, 07041 Alghero, Italy; E-Mail: ivan@uniss.it

* Author to whom correspondence should be addressed; E-Mail: mitraka@iacm.forth.gr; Tel.: +30-2810-391-762; Fax: +30-2810-391-761.

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Abstract: Deciding upon optimum planning actions in terms of sustainable urban planning involves the consideration of multiple environmental and socio-economic criteria. The transformation of natural landscapes to urban areas affects energy and material fluxes. An important aspect of the urban environment is the urban metabolism, and changes in such metabolism need to be considered for sustainable planning decisions. A spatial Decision Support System (DSS) prototyped within the European FP7-funded project BRIDGE (sustainaBle uRban plannIng Decision support accountinG for urban mEtabolism), enables accounting for the urban metabolism of planning actions, by exploiting the current knowledge and technology of biophysical sciences. The main aim of the BRIDGE project was to bridge the knowledge and communication gap between urban planners and environmental scientists and to illustrate the advantages of considering detailed environmental information in urban planning processes. The developed DSS prototype integrates biophysical observations and simulation techniques with socio-economic aspects in five European cities, selected as case studies for the pilot application of the tool. This paper describes the design and implementation of the BRIDGE DSS prototype, illustrates some examples of use, and highlights the need for further research and development in the field.

Keywords: spatial decision support systems; urban planning; sustainability indicators; urban metabolism

1. Introduction

The transformation of landscapes from primarily forest or agricultural uses to urbanised areas modifies energy and material exchanges between the city and its environment. These exchanges define the urban metabolism of a city, which is an important aspect in the functioning of cities [1] and needs to be considered in urban planning. Urban metabolism studies consider a city as a system and distinguish between energy and material flows. Since cities are much more than a mechanism for processing resources and producing wastes, the urban metabolism concept includes livability aspects, referring to the human requirement for social amenity, health and well-being. Sustainability for a city is not only the reduction in metabolic flows, but also the increase of human livability, and economic and social aspects of sustainability need to be integrated along with the environmental ones [2]. The city design (defines the urban form and cover), the urban governance (related to the land use and the anthropogenic emissions) and the local and regional climate dynamics affect the energy, water and carbon exchanges between the urban surface and the atmosphere, modifying the respective urban metabolism components. Therefore, the better understanding and monitoring of energy, water, carbon and pollutants fluxes has the potential to support urban planning and management by: (a) supporting the development of methods for optimization of these fluxes at micro, local and regional scales in the framework of a city-scale climate-change adaptation; and (b) providing the means to support "land-based mitigation", defined as land surface changes producing a modification in urban energy water and carbon exchanges towards slowing the pace of warming in cities. Land-based mitigation complements conventional emissions-based mitigation through addressing the regional to local-scale drivers of climate change that are often the principal driver of ongoing warming trends at these scales [3]. The land-use planning activities of local/regional governments may therefore provide the most direct regulatory means of managing urban energy water and carbon exchanges towards a sustainable urban metabolism, so as to minimize land-based climate, forcing towards the improvement of thermal comfort and air quality, that are both important elements of the quality of life in cities.

Traditional metabolic studies assess the inputs and outputs of food, water, energy, waste, materials, *etc.* from a city, or compare the metabolic processes of several cities [4]. Recent advances in biophysical sciences consider the urban metabolism as the exchange and transformation of energy and matter between a city and its environment, and make possible to provide quantitative estimates of the urban metabolism components at a local scale [5]. Several methods and tools are available for estimating energy, water, carbon and pollutants fluxes, and research efforts in these areas are ongoing. Nevertheless, there is still no standardized method to conduct quantitative urban metabolism studies worldwide [6] and available tools are more scientifically oriented and not user-friendly for planning purposes [6,7]. In addition, comprehensive urban metabolism data at city scale are difficult to obtain, especially for low-income cities. These reasons prevent planners and policy-makers from exploiting existing knowledge and information in urban planning processes.

The rising pressure for urban sustainability confronts planners with the necessity of taking into account the environmental and socio-economic considerations at once. For example, it is not common for urban planners to have background knowledge on urban climatic processes and the interaction with climate experts is difficult because of the different practice backgrounds [5]. Therefore, there is arising need for development of specific evaluation methods and appointed tools to address multiple inter-disciplinary aspects within decision-making regarding urban planning [8]. To support an evaluation, each decision problem needs to be described in a structured way and planning alternatives need to be defined and accompanied by descriptive and quantitative information. Spatial Decision Support Systems (DSS) are powerful decision support tools that comprehensively analyse baseline information and satisfy multiple-period, multiple-objective and multiple-user requirements [9]. Spatial DSS are capable of supporting complex decision-making and of solving semi-structured, or unstructured problems [10]. Such systems help decision-makers in finding concrete solutions for decision issues and facilitate the use of geospatial data and models.

The basis of geospatial decision support is the technology of Geographic Information Systems (GIS). The basic decision supports of GIS include data management to extend human memory, graphic display to enhance visualisation, and spatial analysis functions to extend human computing performance. Beyond these common GIS decision aids, special features include modeling, optimisation and simulation functions required to generate, evaluate, and test the sensitivity of computed solutions. GIS can also support other functions, such as statistical, spatial interaction and location/allocation models. As most territorial and environmental assessments involve several planning alternative options, as well as numerous planners with different views and perceptions, spatial DSS provide effective techniques to assess multiple and/or cumulative impacts, to incorporate stakeholder perceptions and to carry out a vulnerability or suitability analysis in order to evaluate the alternatives under consideration [11]. The use of spatial DSS is lately increasing in impact assessment to support urban planning [12].

The European Seventh Framework Programme (FP7) Project BRIDGE (SustainaBle uRban plannIng Decision support accountinG for urban mEtabolism) introduced the consideration of environmental issues in urban planning support systems, by means of numerical tools. The BRIDGE project did not perform a complete life cycle or a whole system urban metabolism analysis, but rather focused on specific metabolism components, namely energy, water, carbon and pollutants. A corollary of the BRIDGE project was the development of a DSS prototype with the potential to evaluate planning actions that better fit the goal of changing the metabolism of urban systems towards sustainability. State-of-the-art numerical models were employed to simulate the physical flows of energy, water, carbon and pollutants and a Multi-Criteria Evaluation (MCE) approach was adopted to cope with the complexity of interactions between the environmental, social and economic components of the urban metabolism.

The main aim of the BRIDGE DSS is to assist decision-making by providing a structured assessment of alternatives and methods comprising key urban metabolism components for their comparative analysis, ranking and selection among them. An issue to deal with is the dependence of the outcome on the objectives that the user establishes. Different objectives may be set depending on the interests, the needs and the resources of planners and stakeholders, some of which may conflict. Therefore, the optimum solution is a trade-off between objectives, dependent on the end-user (e.g., planner) preferences. The BRIDGE DSS evaluates how Planning Alternatives (PA) modify the physical flows of the urban metabolism components under consideration. To cope with the complexity of urban metabolism issues, objectives are defined in BRIDGE as priorities in relation to interactions between the environmental elements (e.g., fluxes of energy, water, carbon and pollutants) and socio-economic components (e.g., investment costs, housing, employment, *etc.*) of urban sustainability. Indicators, organised in groups, are used to characterise objectives and the evaluation of the performance of each PA is done according to the importance of each objective. The user decides on the relative importance of the objectives and may decide on which indicators to include in the analysis. The combined performance of indicators selected as relevant in each particular case are then used to rank the PA.

The developed BRIDGE DSS prototype and its main components are described in this paper, including the numerical models that were utilised to simulate the physical-flows, the set of indicators developed in the framework of the project based on stakeholder consultation and the MCE approach that was used to evaluate the performance of urban planning actions. Evaluation results for five European cities (Helsinki, Athens, London, Firenze and Gliwice) are also presented and discussed.

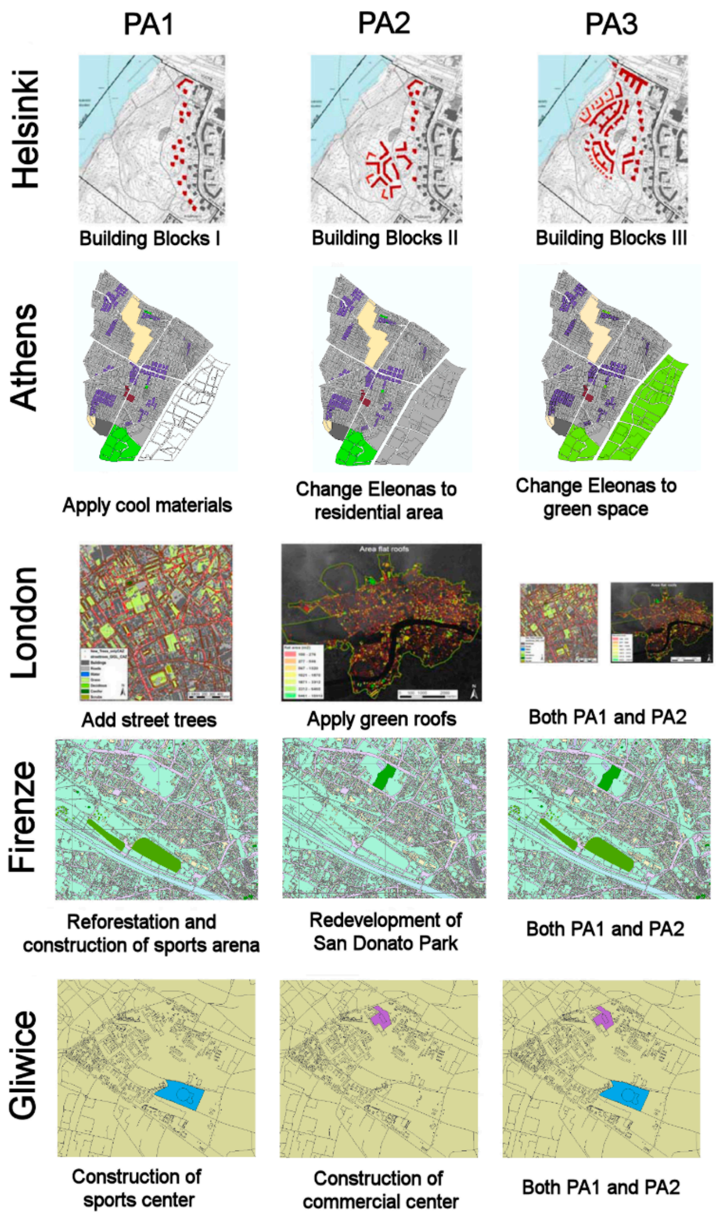
2. Materials and Methods

2.1. Study Sites

Five European cities were selected as case studies in the framework of the BRIDGE project in an attempt to capture different environmental and socio-economic behaviours. Helsinki, Finland, was selected as a high latitude city with rapid urbanisation and the requirement of a substantial amount of energy for heating. Athens, Greece, was selected as a mid-latitude Mediterranean city that requires a substantial amount of energy for cooling. London, United Kingdom, was considered as one of the world's mega-cities. Firenze, Italy, was selected as a representative old city with substantial cultural heritage and Gliwice, Poland, a typical eastern European city with dynamic planning process reflecting the economic, social, and political changes held within last two decades.

Stakeholders and potential users were involved in the design of the BRIDGE DSS from the beginning of the project, forming a Community of Practice (CoP) [13]. The CoP consisted of professionals in the field of city planning and researchers participating in the BRIDGE project to establish a learning environment and jointly search for opportunities for improving sustainable urban planning. The participative approach allowed insight into the case studies to be gained in relation to both planning structures and issues, and sustainability considerations. The approach followed in the BRIDGE project helped to provide the stakeholders and users' perspective to the research team, with the likely outcome that the DSS responds to the sustainability objectives in each city, as well as the needs of the users. The identified objectives and the derived indicators were largely shaped by the professional background and perceptions of the case study representatives.

Figure 1. (**a**) Planning alternatives for the five case studies: (**a**) Helsinki, (**b**) Athens, (**c**) London, (**d**) Firenze and (**e**) Gliwice; adapted from [1].



Three PAs for each case study (PA1, PA2 and PA3) were proposed in the framework of the CoP and are shown in Figure 1. The proposed PA for Helsinki referred to replacing a green area (Meri-Rastila) with different kinds of building types and densities (Figure 1a). For Athens, PA1 referred to applying cool materials on all buildings and roads in a central area (the Egaleo municipality), while the other two alternatives concerned the transformation of a brownfield (Eleonas) to either residential area (PA2), or green space (PA3) (Figure 1b). For London, the PA1 was related to the addition of street trees, PA2 to the installation of green roofs of varying slopes, and PA3 to the implementation of both PA1 and PA3 in the central activity zone (Figure 1c). For Firenze, PA1 concerned the complete reforestation of a green area and a sport arena (in the Cascine Park), PA2 the redevelopment of a former industrial area (in San

Donato Park) and PA3 the implementation of both PA1 and PA2 (Figure 1d). Finally, for Gliwice, PA1 regarded the construction of a sports centre (Gliwice Central Arena), PA2 the construction of a commercial centre and PA3 again referred to the implementation of both PA1 and PA2 (Figure 1e).

Although all five case studies represent distinct urban structures and planning issues, and the proposed planning alternatives significantly diverge amongst cities, sustainability is at the core of urban planning in all the cities. The planning objectives contemplated in the relevant development plans and the policy priorities identified during the CoP (e.g., addressing greenhouse gas emissions and climate change by enhancing the urban fabric and the energy-efficiency in buildings; reducing traffic-related emissions through improvements in public transport; or/and increasing urban green spaces to address air quality and heat island effect and the associated health implications) illustrate a common line of improvement and promotion of sustainability principles at a European level [12].

2.2. Physical-Flow Numerical Models

Physical-flow numerical models (referred simply as models from now on) were used to simulate the exchange of energy, carbon and pollutants fluxes in urban areas. A large variety of such models exists, from those using simple approximations to very complex ones and the selection and application of specific models depends on the computer power availability, the available data and the objectives of the study. Different types of models from mesoscale air quality models to urban canopy models were implemented, using the cascade modeling technique from large to local scale. Mesoscale meteorological models such as WRF (Weather Research & Forecasting Model) were used to simulate the atmospheric flow in a 3D cube with spatial resolution between 0.2–100 km within domains from 10 km and 50 km to thousands of km [14]. WRF models produced detailed information of all meteorological variables and fluxes involved in the atmospheric flow. Meteorological and atmospheric condition information estimated by WRF provided inputs to chemical transport models such as CAMx (Comprehensive Air Quality Model with Extensions) [15], CHIMERE (Chemistry-transport model) [16] and CMAQ (Community Multiscale Air Quality) [17], which were used to estimate the atmospheric content of carbon and pollutants.

In addition to the application of complex and demanding models, urban canopy models were also used in BRIDGE. These models use less complex approximations, are less demanding in terms of computations and easier to use in decision support tools. Urban canopy models of different turbulence schemes such as LUMPS (Local-scale Urban Meteorological Parameterisation Scheme) [18] and SURFEX (Town Energy Balance—SURFace-atmosphere EXchange Module) [19] were applied for energy, carbon and pollutants fluxes approximation. The ACASA model (Advanced Canopy-Atmosphere Soil Algorithm) [20] was simulated surface-atmosphere interactions and the distribution of trace gases. The second generation Gaussian plume model URBAIR model (Urban Air Quality) [21] was used to evaluate air quality and dispersion patterns, since it is appropriate for distances up to about 10 km from the source. Finally, the SIMGRO model (SIMulation of GROundwater and surface water levels) [22] was used to produce detailed information on all the hydrological processes present in an urban environment. The different model simulations performed for the BRIDGE case studies, generated outputs like the CO_2 flux, CH_4 emissions, PM10, O_3, SO_2 concentrations, sensible and latent heat flux *etc.* A set of aggregation algorithms were developed and applied to estimate absolute indicator values from the model's simulation results, depending on the nature of each indicator.

2.3. Data Collection and Organization

To support both the modeling procedure and the PA evaluation process, data associated to both environmental and socio-economic parameters were collected for the five case studies [23]. Energy, water, carbon and pollutants fluxes were systematically monitored, using both in-situ and remote sensing techniques. Surface fluxes and latent heat, momentum, net urban carbon exchange and aerosols fluxes were measured on a continuous basis by eddy covariance/large aperture scintillometry and by repeated seasonal campaigns of research aircrafts. Both existing and new networks of bio-sensors were used as bio-accumulators assessing air quality. Collected data were used to validate the simulations generated by the models. Satellite, airborne and ground-based remote sensing methods were applied to derive spatial distributions of various geo-physical parameters such as surface albedo and emissivity. These were necessary as input to the models. Additional data were gathered referring to traffic flows, soil and vegetation status and activity, soil moisture, energy exchange and air quality of buildings, surface temperature, indoor pollutants and Particulate Matter (PM) concentrations. The land cover/use dynamics were also estimated and mapped. Socio-economic data concerning parameters like space, mobility, heat and water demand, land-use types, coverage and intensity, building volumes, population density, unemployment rate and education level were also gathered. All the above-mentioned data, along with the model simulation results were organised in databases for the case studies and are part of the BRIDGE DSS.

3. Algorithms Description and Implementation

3.1. Algorithms Description

The overall goal of the BRIDGE DSS was to assist urban planners to better explore the decisions at hand and to analyse the trade-offs between the competing criteria to consider urban metabolism in planning decisions. Therefore, the adapted methodology is based on sustainability objectives defined for specific aspects of urban metabolism. These objectives reflect components of sustainability, namely environmental, social and economic. A set of criteria were associated to the objectives providing a link between the objectives and the indicators. Indicators demonstrate the level of achievement of each criterion in a quantified manner. They intend to reflect the multidimensional nature of the urban metabolism, while making them easily understood by non-experts. The set of indicators developed in the framework of CoPs in BRIDGE project is listed in Table 1 [12]. These indicators are grouped into three main categories that depict the sustainability dimensions of urban metabolism and they are further sub-grouped in a hierarchical mode. This hierarchical grouping allows inclusion of a group or subgroup of indicators at will in the analysis, and accordingly, to adjust their relative importance, providing flexibility concerning the level of detail or aspects considered in the analysis.

The DSS allows the user to decide upon the sustainability objectives according to user needs or preferences and to determine their relative importance. The evaluation of the performance of each PA is done in accordance with the predefined qualitative values (*i.e.*, relative importance) for each criterion to measure the performance of individual alternatives. The developed MCE is then used to measure the intensity of the interactions among the different elements in the system. Different algorithms are used to aggregate the models simulation results, at both geographic (*i.e.*, intervention area and surroundings) and temporal (e.g., annual) levels, resulting in absolute indicator values. Thresholds are used in some cases to establish the status of the indicators' performance, which refer to the maximum values permitted according to legislation. For example the upper limit for PM10 is 50 μg/m^3, not to be exceeded more than 35 times a calendar year, according to European Directive 2008/50/EC [12]. Model simulations would provide the PM10 concentration per area for a given time interval. The aggregation algorithm counts the times of 50 μg/m^3 threshold exceedance throughout the calendar year and creates an "indicator map of exceedances". The map indicates the areas where the threshold was exceeded more than 35 times in a year. The computed indicator values are then used in the MCE algorithm to retrieve appraisal scores, as explained below.

Table 1. Set of indicators that are used in the SustainaBle uRban plannIng Decision support accountinG for urban mEtabolism (BRIDGE) Decision Support System (DSS) Prototype; adapted after [12].

Environmental Indicators	**Social Indicators**
Energy	*Land Use*
Energy consumption by cooling/heating (kWh/m^2); Anthropogenic heat (W/m^2); Bowen ratio (unitless); Percentage of energy from renewable sources (%)	New urbanized areas (m^2); Brownfields re-used (m^2); Density of development (built m^2/total m^2)
Thermal Comfort	*Mobility/Accessibility*
Thermal Comfort Index (Cooling Power); Air Temperature (°C); Number of days above threshold (days/total period)	Quality of pedestrian (qualitative); Length of cycle-ways provided (m); Length of new roads provided (m); Use of public transport (% of total population); Number of inhabitants with access to public transport (inhabitants within 500m of public transport)
Water	*Social Inclusion*
Water consumption (mm^3); Evapotranspiration (mm^3/m^2); Infiltration (mm^3/m^2); Surface run-off (mm^3/m^2); Potential flood risk (peak mm^3/m^2 discharges)	Number of inhabitants with access to services (inhabitants/m^2); Number of inhabitants with access to social housing (inhabitants/m^2)
Air Quality	*Human well-being*
NOx, PM10, PM2.5, O_3, CO, SO_2 concentrations (μg/m^3); NOx, PM10, O_3, SO_2exceedances (threshold exceeded or not); NOx, PM10, O_3, SO_2Potential Population Exposure	Number of inhabitants affected by flash flooding (No. of inhabitants); Number of inhabitants affected by heat waves (No. of inhabitants)
Greenhouse Gases	*Economic Indicators*
CO_2, CH_4Emissions (tonnes)	Cost of proposed development(€ or €/m$_2$); Effects on local economy (No. of new jobs created); Effects on local economy (€ or €/m$_2$)

For overcoming problems like simulation uncertainties and the lack of precise socio-economic information regarding the PAs, the developed MCE method compares between alternatives rather estimating absolute appraisal scores. One of the possible PAs is considered as the baseline or reference, which is set by the user—so the other alternatives are compared to that of the reference alternative could be the actual situation (business as usual scenario, where no intervention is done in terms of planning actions), or one of the proposed PAs. Having the indicator values estimated for all PAs, indicator scores are then calculated. Indicator scores (Si) depict their performance compared to the reference situation, and they are calculated taking into account the changes to the indicator value introduced by the PA being analysed (I_{PAi}), compared to the reference situation adopted (I_R). If x stands for the PA in question and R stands for the reference situation, the ith indicator's score is derived using Six = I_{ix}/I_{iR}. The reverse form of the formula ($S_{ix} = I_{iR}/I_{ix}$) is used for indicators having a "positive effect" in sustainability, like for example the "area of green spaces" indicator, which has a positive effect on sustainability if its value is increased).

The user's preferences concerning indicators are defined by weights. Weight is a numeric amount assigned to an indicator, indicating its relative importance in relation to other indicators in the decision situation. The higher the weight, the more important a given indicator is considered. Established weights are normalised, so that their sum in all indicator groups equals one. Weights in BRIDGE DSS are assigned in pairs, defining the relative importance of indicators and indicator groups [24]. Qualitative terms shown in Table 2 are used to assess the relative intensity of preference between two elements. Taking pairs of indicators and asking two questions (e.g., which indicator is more important, C_i or C_j, and how much more), square reciprocal matrices are generated. For a matrix A the element a_{ij} represents the weight given by the user for indicator i compared to j [25]. The diagonal of matrix A is 1 (indicating that each element is the same importance with itself) and $a_{ji} = 1/a_{ij}$. As noted above, the weights w_i are normalised to ensure that the sum of weight equals one, by estimating the eigen vectors v of the maximum eigen value λ of matrix A and then normalising by

$$w_i = \frac{v_i}{\sum_{i=1}^{n} v_j} \tag{1}$$

The scores of indicator groups are calculated using a Cobb-Douglas function combining indicators' scores and their weights, which are defined by the user according to their relative importance. Each group's score (S_n) is given by

$$S_n = S_1^{w_1} \cdot S_2^{w_2} \cdot S_3^{w_3} \cdot \ldots \cdot S_k^{w_k} \tag{2}$$

where S_i is the ith indicator score, w_i is the ith indicator's weight and k is the number of indicators included in the group. One of the advantages of this type of functions is that it enables dealing either with relative or absolute values of indicators, and it is sensitive to the changes in scores (*i.e.*, indicator performance) as well as in weights (*i.e.*, indicator importance/significance). The overall score of each PA is calculated in the same way as the groups' scores, using a function of groups' scores and weights.

In summary, it is based on a value function using scores and weights: the first one translates the relative performance of the PA under evaluation when compared to a reference situation; while the second translates the relative importance of indicators (or indicator groups) ascribed by the user. The BRIDGE DSS results are more than just one appraisal score for each PA. The final appraisal score is just a representation of all the collected information. No confidence measures regarding estimated scores are necessary to compute, because the methodology is based on relative rather than absolute values. The user can assess individual indicator scores, as well as scores of indicator groups, to examine their performance related to the reference situation. Absolute indicators values can also be visualised, in the form of maps to reveal their geographical and temporal variability.

Table 2. Verbal terms shown in the table below are used to assess the intensity of preference between two elements (adapted after [24]).

Value	Verbal Term
0	same importance
1	slightly more important
2	weakly more important
3	weakly to moderate more important
4	moderately more important
5	moderately to strongly more important
6	strongly more important
7	greatly more important
8	absolutely more important

3.2. Implementation

The BRIDGE DSS prototype was developed based on the above described algorithms using Visual Basic programming language and exploiting the available data that were organized in SQL databases. A Graphical User Interface (GUI) was developed as an add-on for ESRI ArcGIS [26] to fully exploit its capabilities on handling geographical data. The role of the GUI is to facilitate the user in selecting the indicators to be used in the analysis as well as to define their relative importance; it is also used for the presentation of the analysis results. An ArcGIS toolbar was created including all menus and options necessary for the implementation of PA evaluations.

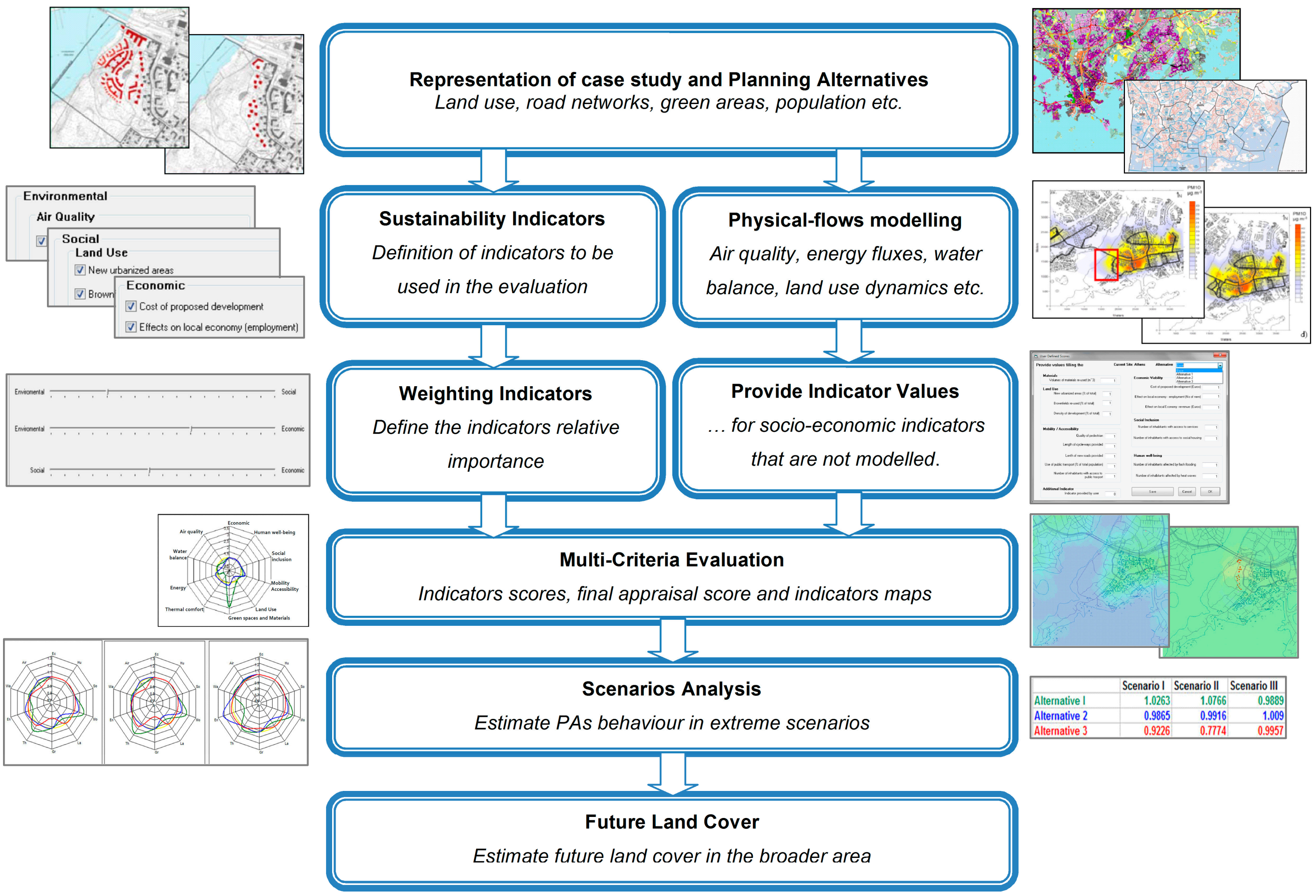
Some of the models that were used in the BRIDGE DSS were very demanding in terms of computation power (e.g., WRF model) and this made it impossible to integrate them directly into the developed prototype. Those models can only run in powerful cluster computers; this impeded their integration in the DSS prototype. For the BRIDGE project, model simulation were performed for all the case studies (and their PAs) for a period of one year (hourly time step), and the simulation results were organised in databases which were then integrated into the DSS so they could be accessed for evaluation. BRIDGE databases are structured in order to make them easily accessible by the end-user, by means of the developed GUI, as well as to make it possible to visualise spatio-temporal information in different ways. For the models that were directly integrated in the system (e.g., URBAIR), the user can interfere, parameterise and run at will.

The nature of PA, derived from the CoPs (Figure 1), was different for each case study and thus different implementations were used in the numerical models. The PA for each case study needed to be interpreted so as to fit the specifications of both the models and the system. For Helsinki, the PA were implemented by changing the land uses from green areas to urban areas in the location of new buildings. For Athens, PA1 was implemented by setting the albedo value of buildings to 85% and of roads to 45% and PA2 and PA3 were implemented by changing the land uses of Eleonas from industrial/commercial urban areas to high density urban and grassland respectively. To implement the PA for London, since seven land cover types (buildings, roads, water, grass, conifer, deciduous, shrubs) were considered, a correspondence between the above land cover information and land use types used by the models was established. To take into account the new street trees and green roofs, modifications of the following parameters were made: roof width, road width, and fraction of urban by type. For Firenze, PA1 was implemented by changing land use from sport hall and grassland to deciduous trees, PA2 was implemented by changing land use from industrial to grassland and PA3 was the implementation of both PA1 and PA2 at the same time. For Gliwice, PA1 was implemented by changing the land use from commercial to high density urban area, PA2 was implemented by changing the land use from low density urban to high density urban area and PA3 was the implementation of both PA1 and PA2.

3.2.1. MCE Procedure

In this section, the procedure of how to run an evaluation using the BRIDGE DSS prototype is described in order to present the system's functionalities. The procedure is graphically represented in Figure 2. The first step in the evaluation procedure is the selection of a specific case study to proceed with. Description of the PA is provided by the system along with the respective spatial data that feature each PA.

Figure 2. Chart depicting the Planning Alternatives (PA) evaluation procedure used in the BRIDGE DSS prototype.



Subsequently, the user needs to define the indicators to be included in the evaluation. The list of the available hierarchy of indicators is presented in a structured way, as shown in Figure 3, and the user is asked to select among them. The hierarchical organisation of indicators in three main groups related to environmental, social and economic dimensions of sustainability can be observed in this structure. All levels of the hierarchy can be accessed through this window. The relative importance of indicators (and indicator groups) can be defined through this menu using scale bars on the basis of the qualitative terms of Table 2. An example of such a scale bar is shown in Figure 4. If no user preference is set, the indicators are considered of equal importance in the evaluation process. This means, for example, that the indicators in question are all equally important and therefore given the same weight. Tables of normalised weights are computed using the previously described algorithm.

Figure 3. Window for selecting indicators to be used in the evaluation analysis. The indicators hierarchy, shown also in Table 1, is depicted in this selection window.

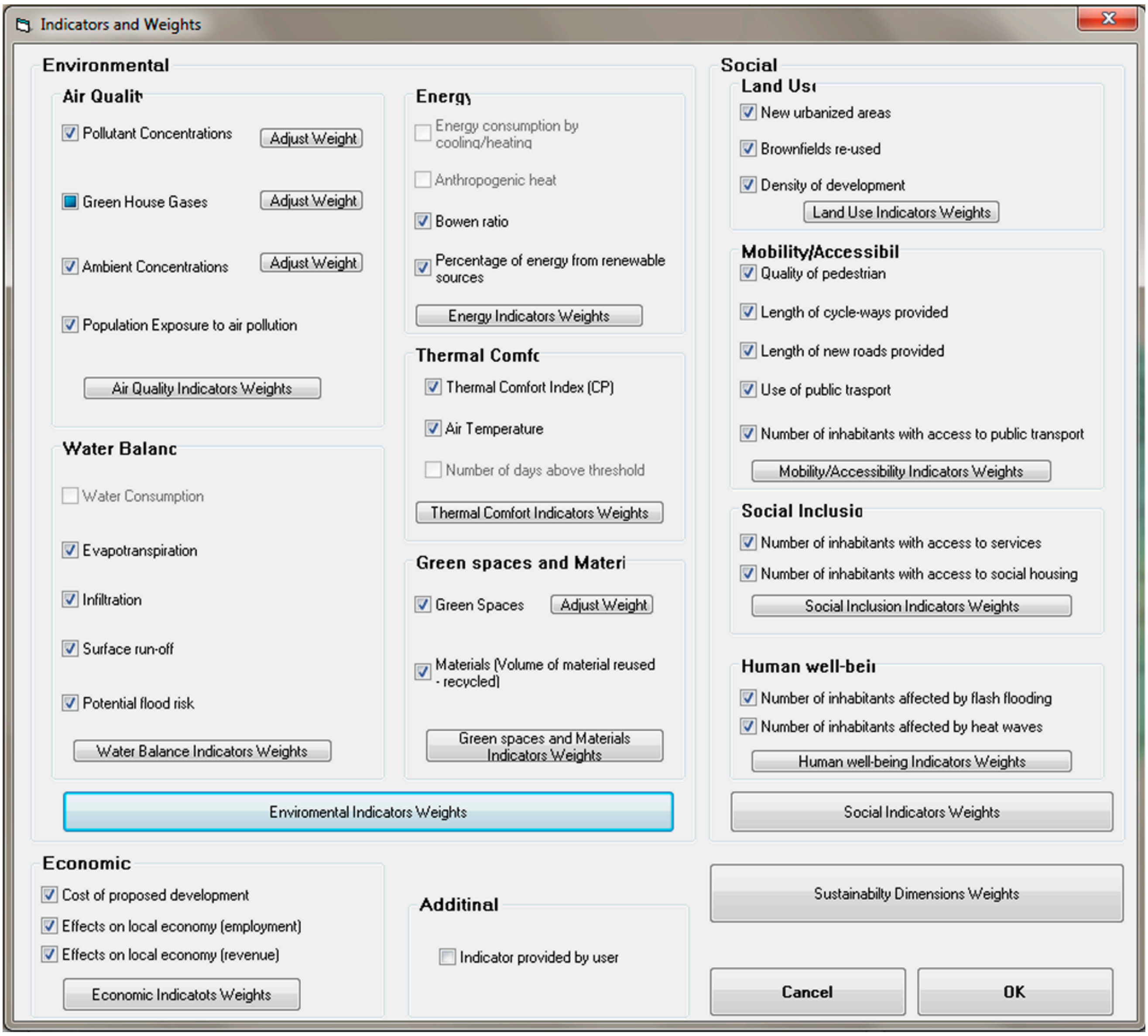
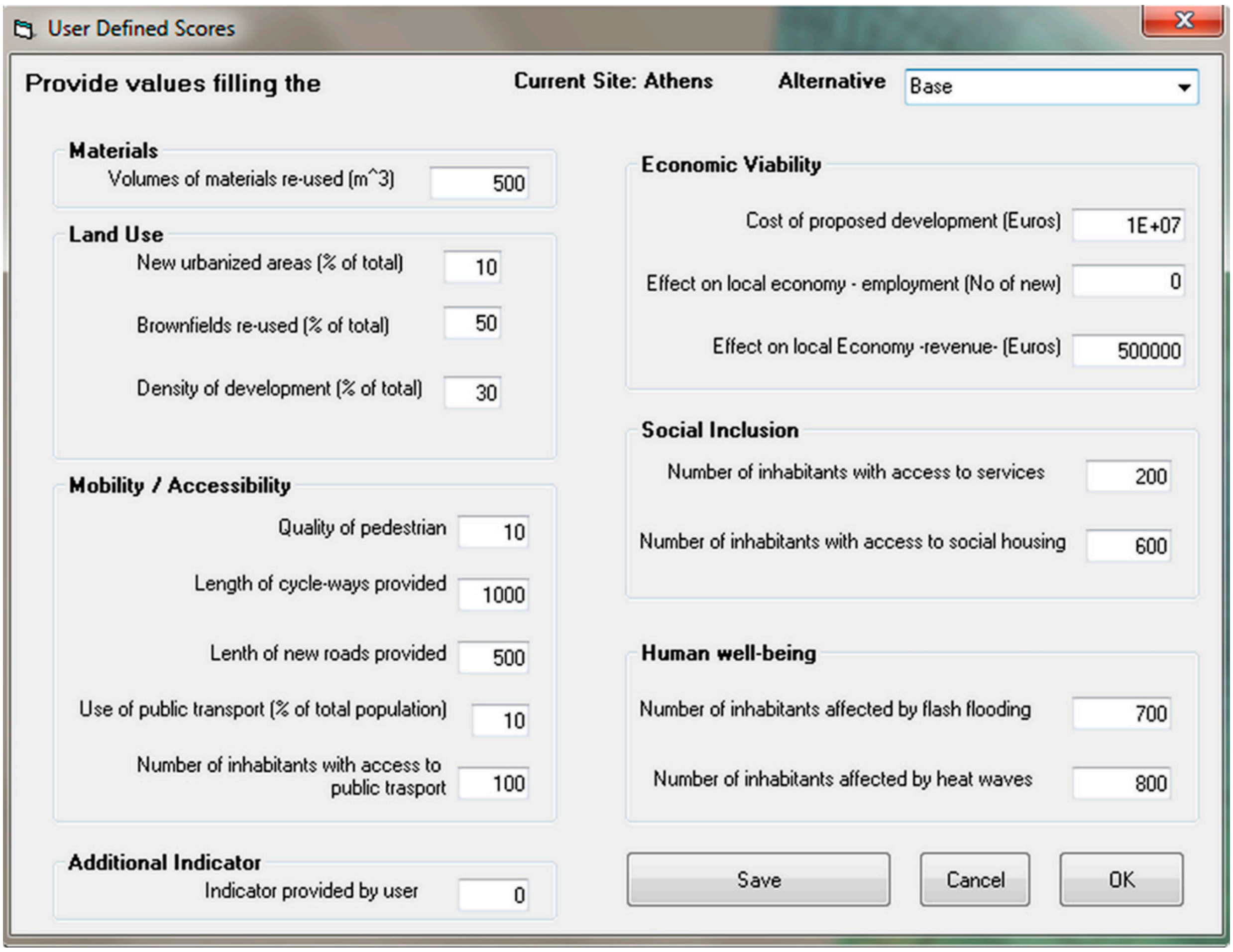


Figure 4. (**a**) Example of scale bars that are used to define the indicators' (or indicator groups') relative importance and (**b**) the normalised weights that are computed based on the user's preferences.

Figure 5. Form that is used for insertion of indicator values that are not modeled in the BRIDGE DSS (*i.e.*, socio-economic indicators).



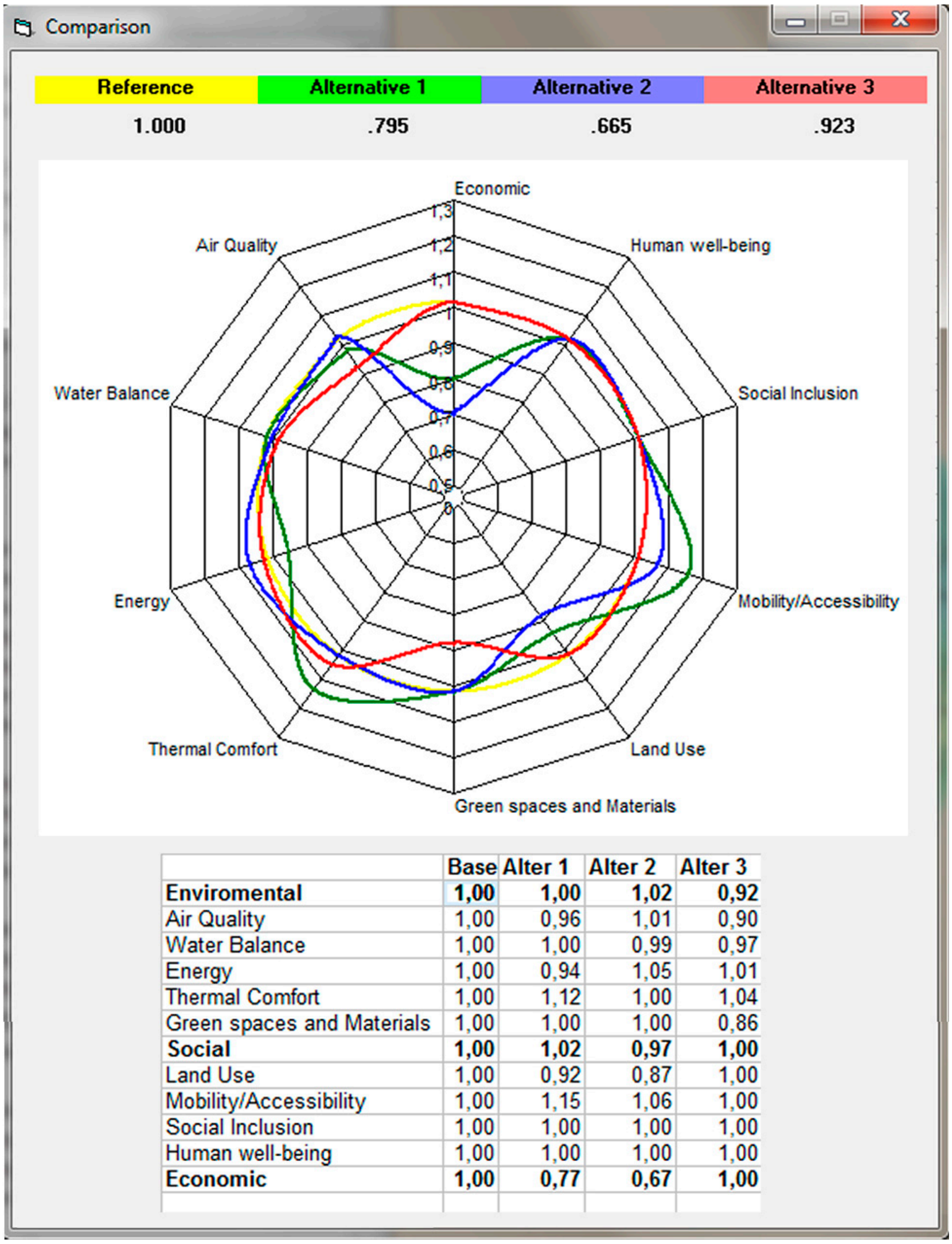
The next step is the calculation of selected indicator values for each PA. These values are calculated in different ways. Environmental indicators arising from physical flow simulations are calculated by numerical models, while socio-economic indicators reflecting objective values (e.g., number of houses constructed, number of jobs created, *etc.*) are given as data attached to planning alternatives and thus have to be directly inputted by the user. Socio-economic indicator values are not estimated using models in the BRIDGE DSS, as the integration of socio-economic models was out of scope of the BRIDGE project. Therefore, the user is required to provide these values for each PA, using the form shown in Figure 5. There is a choice of providing absolute or relative values. Relative values reflect the relative performance of indicators between the PA in question and the reference situation. Relative values are useful when the absolute values of indicators cannot be defined (e.g., regarding employment indicator, one may not know how many job positions will a PA induce, but might estimate that this be double to the reference situation). Instructions on how to use relative values instead of absolute ones are given in the BRIDGE DSS Prototype User's Guide [27]. Once all the above-described information is made available to the system, the user can run the MCE procedure. A set of different outputs are produced to estimate the PA performance in terms of indicators. The representation of the results is described in the following section.

3.2.2. Evaluation Outputs

The evaluation procedure calculates individual indicator scores, as well as a final appraisal score for each PA. Spider diagrams are used to graphically represent the individual indicator scores of all PA, illustrated in different colors to facilitate comparison. The reference situation is always presented as a circle in the spider diagram, having all appraisal scores equal to one. A final appraisal score for each PA is calculated as a combination of the above scores and weights, as described in the previous section. A final appraisal score higher than one indicates better performance of the PA in question, compared to the reference. The same applies to the underlying indicators scores. Figure 6 shows an example of the evaluation results form. The final appraisal scores for the PA are shown on the top of the window, while the individual appraisal scores are shown on the right. This information is not considered sufficient for taking a decision regarding the best PA, thus the user can also visualise individual indicator maps to have a clear picture of the spatial and temporal distribution of specific indicator values.

Indicator maps are spatio-temporal representations of the indicator values computed in each grid cell using the model simulation results. The desired time period of indicator values to be displayed can be adjusted by the user. The user selects the indicator of interest from a list of available indicators, and the desired time period. Different combinations of time and days can be used to produce different kind of maps (i.e. seasonal maps, daily maps, yearly maps, *etc.*). The type of performed calculations can also be assessed through time and the user can choose between average, minimum, maximum and summary values to be drawn in the relevant indicator map, which is considered necessary due to the differences in the nature of indicators (e.g., EU air quality Directive's reference to annual *vs.* daily values). The option to draw maps of differences between the PA and the reference situation is also provided, which aims at highlighting the differences between PA enabling their comparison.

Figure 6. Example of the Multi-Criteria Evaluation (MCE) result form, depicting the final appraisal score of each PA, the individual computed scores and the spider diagram that graphically depicts the different scores for different PAs.



	Base	Alter 1	Alter 2	Alter 3
Enviromental	**1,00**	**1,00**	**1,02**	**0,92**
Air Quality	1,00	0,96	1,01	0,90
Water Balance	1,00	1,00	0,99	0,97
Energy	1,00	0,94	1,05	1,01
Thermal Comfort	1,00	1,12	1,00	1,04
Green spaces and Materials	1,00	1,00	1,00	0,86
Social	**1,00**	**1,02**	**0,97**	**1,00**
Land Use	1,00	0,92	0,87	1,00
Mobility/Accessibility	1,00	1,15	1,06	1,00
Social Inclusion	1,00	1,00	1,00	1,00
Human well-being	1,00	1,00	1,00	1,00
Economic	**1,00**	**0,77**	**0,67**	**1,00**

3.2.3. Further Analysis of MCE Outputs

While the discussion so far has emphasized the capabilities and functionalities of the DSS to evaluate the impact of local-scale PA, these alternatives do not live in a vacuum, or better, they should not be assumed to exist against astatic backdrop. A fair evaluation of projects thus must take into account the evolution, the possible trajectories and future scenarios of the wider urban context, and indeed possibly the whole urban area. That is why BRIDGE DSS features two additional future-scenarios analysis against which (and in the context of which) the PA are evaluated.

The first scenario analysis tool is based on a land-use cellular automata (CA) model, integrated in the BRIDGE DSS prototype. The purpose of the model is to simulate the city-wide land use dynamics, and thus produce scenarios (under different parametric assumptions about the city growth and demand for land uses) of future spatial distribution of city-wide land uses. The model is based on the conventional model of constrained cellular automata, which allocates the demand for land uses to each cell by accounting for the interaction between different land uses and physical, environmental and institutional factors (e.g., zoning, planning regulations) related each cell [28]. Thus, the CA model allows to account for broader effects of planning decisions, in terms of a spatial distribution of land uses over a larger geographical area.

The second wide-scale scenario-analysis tool incorporated in BRIDGE DSS allows the user to evaluate priorities in response to different extreme future scenarios. Three extreme future strategic scenarios were considered in the BRIDGE project, as shown in Table 3 [29]. In Scenario I, climate change is not a threat, there are sufficient energy resources and the cities' success depends on their ability to attract qualified people and firms. Critical issues for sustainability in this case may refer to the efficient use of energy, the transition to renewable resources and cleaner use of fossil energy, as well as attempts for a balanced society and a highly productive economy. In Scenario II, climate change is a burning issue. The cities' attractiveness depends on their capacity to face climate change, while energy is not that big a problem and the economy is growing. To face the climate change threat there is urgent need to absorb greenhouse gases and to reduce the emissions. In Scenario III, the lack of energy is freezing the economy, thus cities' success depends on low costs and energy shortage. Non-renewable sources are reaching the end and the use of renewable sources is insufficient. Reduced mobility leads to urban concentration, resources are diverted for fast increase of renewable energy sources and social inequality is increased.

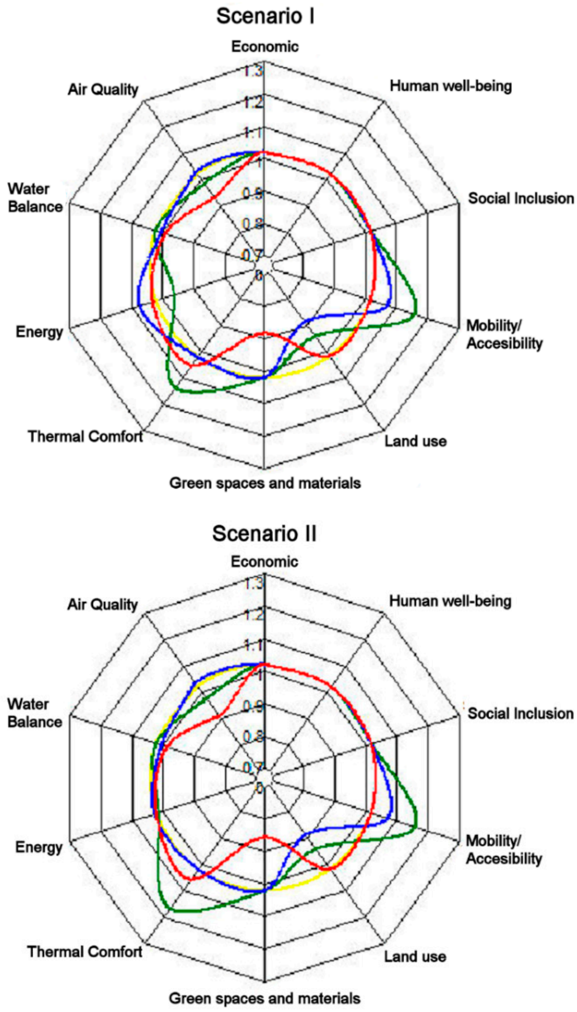
Table 3. Extreme future scenarios, as these are defined in BRIDGE.

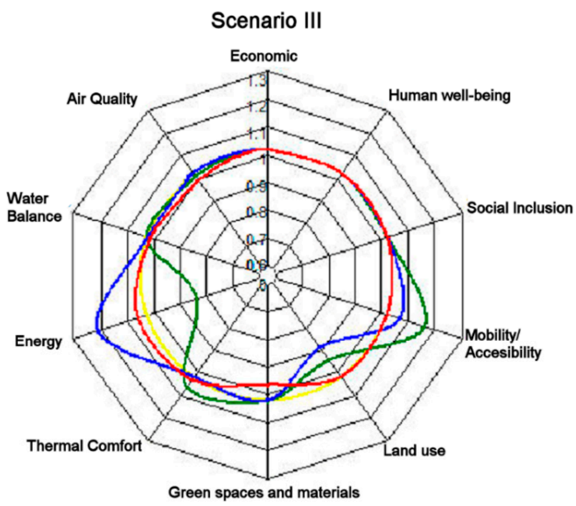
Scenarios	Climate Change	Energy/ Technological Development	Economy
Scenario I: BRIDGE in Wonderland	+	+	+
Scenario II: Climate change is a burning issue	-	+	+
Scenario III: Lack of energy in freezing the economy	+	-	-

Model projection for the year 2030 allowed assessing the performance of the environmental indicators for the reference situation and for all PA considered under each of the considered future scenarios. For these projections, assumptions on environmental conditions were made, based on the Intergovernmental Panel on Climate Change (IPCC) scenarios A2, A1F1 and B1 [30], which address the characteristics of the strategic scenarios developed in the BRIDGE project. More specifically, the IPCC scenario A2 (medium emission scenario) was used in the BRIDGE models to simulate the fluxes in case of the Scenario I, the IPCC scenario A1F1 (worst emission scenario) was used in case of Scenario II, whereas the IPCC scenario B1 (best emission scenario) in case of Scenario III [29,31].

For the evaluation of PA against the strategic scenarios, the environmental indicators scores were calculated based on model simulation results for the year 2030. As noted above, model simulations were performed using the IPCC scenarios, whereas the estimations of socio-economic indicators values were defined by the CoPs. In the absence of environmental, energy and economic constraints, the focus of urban policy would be the prevention of other types of problems, and the increase of quality of life in general. The evaluation of the PAs in each case study against strategic scenarios is done by adjusting the indicators relative importance considering the extreme situation outlined by the each scenario. Windows identical to those used for adjusting indicators relative importance for the present conditions (Figure 4) can be used to adjust the indicators' weights. The MCE process, adjusted for the extreme conditions of scenarios and the new user preferences, runs again and results are produced for each strategic scenario as shown in Figure 7.

Figure 7. Example of the scenario analysis result form.





	Scenario I	Scenario II	Scenario III
Alternative 1	1.0263	1.0766	0.988
Alternative 2	0.9865	0.9916	1.000
Alternative 3	0.9226	0.7774	0.995

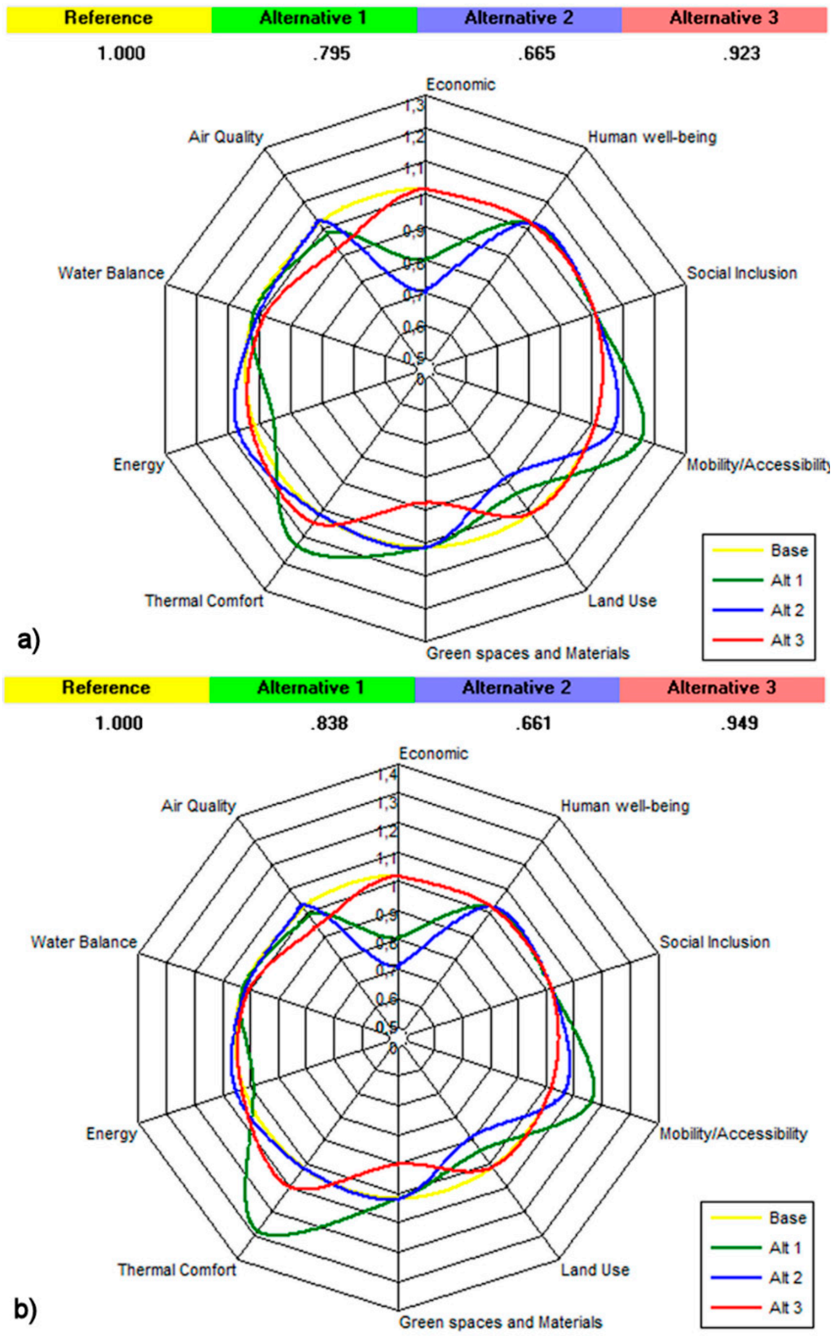
4. Results and Discussion

The BRIDGE DSS prototype was developed with the potential to evaluate PA and determine the alternative that better fits the goal of changing the metabolism of urban systems towards sustainability. Examples of this DSS results are presented and discussed in this section, aiming at highlighting the system's main capabilities and advantages, as well as the limitations and the induced need for further research.

The BRIDGE DSS assesses the performance of a PA in terms of sustainability according to the user preferences. As an example, Figure 8a shows the estimated MCE results for the case study of Athens, with all the indicators included in the analysis having equal importance. In this case PA3 was found to have the highest final appraisal score (0.923), compared to the reference alternative, followed by PA1

(0.795) and PA2 (0.665). However, if the user changes the relative importance of some indicators the results change. For instance, given that Athens' citizens face thermal discomfort issues quite often during summer, a possible user might consider thermal comfort to be absolutely more important than water and energy balance. In such cases, as it can be noted in Figure 8a, PA1 gains a higher appraisal score in terms of thermal comfort (1.12) than PA2 (1.00) and PA3 (1.04). By changing the user's preferences in this way, the individual and final appraisal scores also change (Figure 8b), but PA3 remains with the highest final score (0.949), followed by PA1 (0.838) and PA2 (0.661). This example demonstrates the performance of the MCE algorithm used in the BRIDGE DSS.

Figure 8. MCE results for the PAs of Athens as estimated by the BRIDGE DSS (**a**) by applying equal importance to indicators and indicator groups, (**b**) by changing the importance of thermal comfort as absolutely more important compared to energy and water balance.

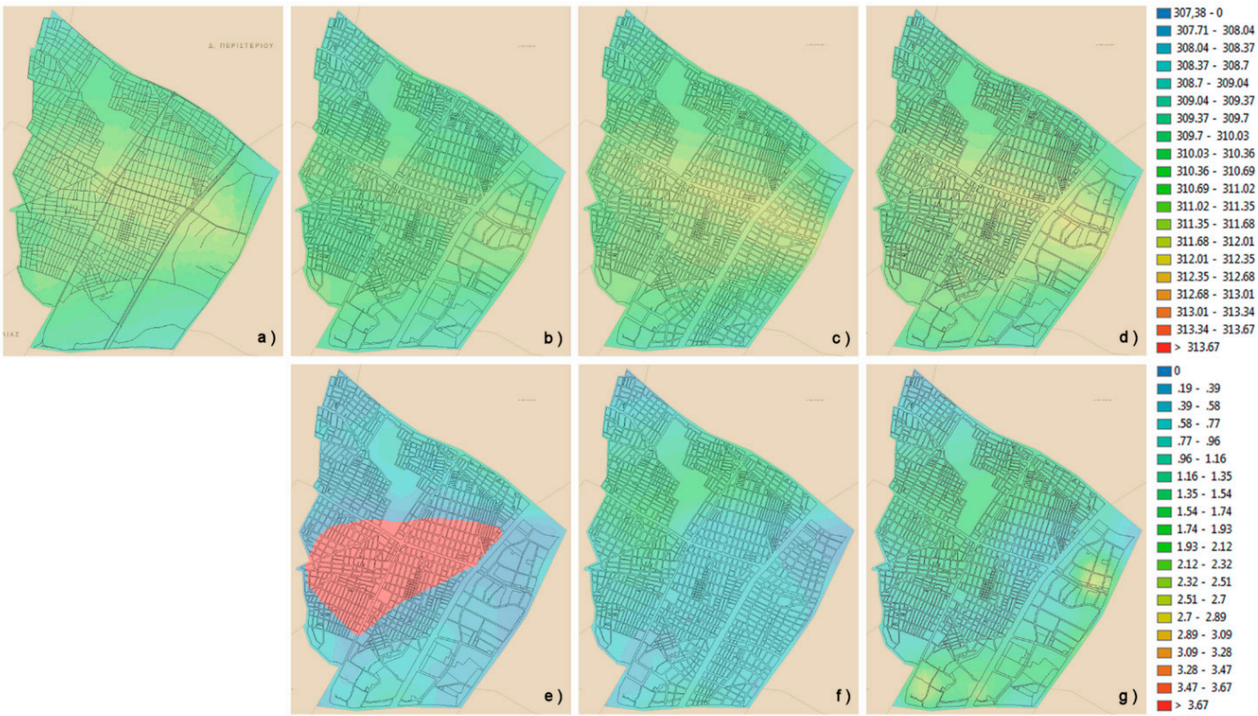


a)

b)

Additional tools are provided by the BRIDGE DSS in order to assess the behavior of the PA with regard to the availability of indicators in space and time. The desired indicator along with the time period can be selected by the user according to a given interest for more detailed examination. Figure 9 shows the spatial distribution of air temperature in the case study of Athens for the reference situation and for each PA (top of the figure) for a summer period between 10:00 and 13:00. The capability of visualising differences between the reference situation and the PAs is also provided by the system. This capability enables automatic identification of spatial differences as well as quantification of those differences. Figure 9 (bottom) shows differences of air temperature between the PAs and the reference situation for the same time period.

Figure 9. Air Temperature indicator map for the case study of Athens: Spatial distribution of air temperature maximum values for the reference situation (**a**) and for each PA (**b**–**d**) for summer period between 10:00 and 13:00. The differences between the reference situation and each PA are also illustrated (**e**–**g**).



Legislation exists to ensure good air quality in urban areas (*i.e.*, the European Directive 2008/50/EC). The established restrictions refer to concentration limits in the area, specifying also the permitted time limit. Spatial and temporal patters of indicators referring to exceedances of established limits are also estimated by the BRIDGE DSS. Such indicator values and their temporal and spatial distribution are highly useful for urban planning actions. Figure 10 shows an example of exceedances in the case study of Helsinki, for the reference situation (a) and the PAs (b–d). Red cells represent areas where the threshold has been exceeded for atmospheric Particulate Matter of diameter of 10 μm or less (PM10).

Figure 10. Example of indicator map of exceedances. Number of exceedances of PM10 threshold in the area of Helsinki for (**a**) the reference situation, (**b**) PA1, (**c**) PA2 and (**d**) PA3. Red cells represent the areas where the established EU threshold is exceeded, at least one time, during a time period of one year.

In addition, the BRIDGE DSS allows the evaluation of PAs in three strategic scenarios (Table 3). The evaluation of PAs in extreme future conditions aims at characterising the PAs as either robust, unstable, or unclear. Robust alternatives are those that present the best score in all situations, unstable results regarding the strategic scenarios analysis are considered those that require deepen knowledge about future evolution before a decision is taken, while an unclear evaluation is characterised as one where the appraisal scores are very similar, indicating the need to use more and better information. For example, Table 4 shows the results of strategic scenarios analysis of the case studies of Gliwice and Helsinki. It is clear that for Gliwice, the PA3 was the robust option: whatever the context where the political decision is taken, the best alternative was the construction of both the sports centre and centre of new technologies. However, concerning Helsinki, the PA presented similar performances in the three strategic scenarios. When there were no economic or environmental constraints in the scenarios, the results for all scenarios were almost equal: there were no clear gains of increasing the constructed area. For strategic scenarios II and III, the results pointed to the project with more inhabitants and built up area (PA3), but with a marginal advantage over PA2.

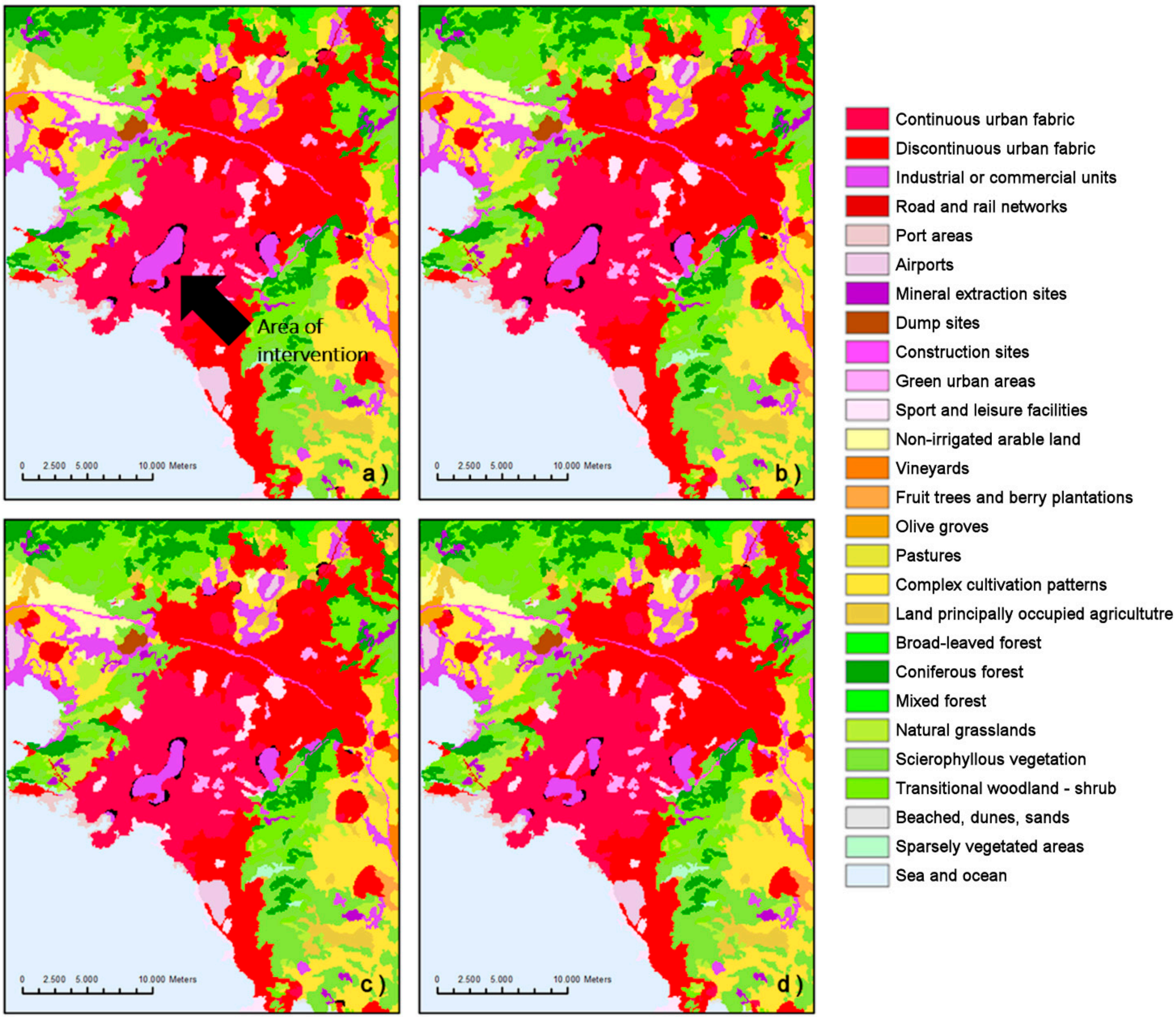
Another tool, embedded in the BRIDGE DSS is the cellular automata module. This module allows the user to estimate future land uses in the broader area, taking into account the foreseen planning action.

Figure 11 shows an example of change in the land uses in the next two decades in Athens with and without the implementation of the PAs shown in Figure 1. The cellular automata is useful for assessing the effect of a planning intervention on the land uses of the surrounding areas for a longer time period. In the case of Athens for example, PA1 does not have any effect on land uses since it only refers to changes in materials used for the same structures. On the other hand PA2 and PA3 do result on some land use changes, but only close to the area of interventions.

Table 4. Strategic Scenarios evaluation results for Gliwice and Helsinki.

Case Study	Scenario	PA1	PA2	PA3
Gliwice	Scenario I	1.00	1.01	1.33
	Scenario II	1.00	1.02	1.05
	Scenario III	1.00	1.08	1.37
Helsinki	Scenario I	1.00	0.99	0.98
	Scenario II	1.00	1.10	1.12
	Scenario III	1.00	1.14	1.15

Figure 11. Estimated future land uses for the case study of Athens for (**a**) the reference situation, (**b**) PA1, (**c**) PA2 and (**d**) PA3.



The BRIDGE DSS also allows the user to parameterise and run some models. Those models, as mentioned earlier, are not highly demanding in terms of computation. The attempt of developing such a prototype illustrated the restrictions of implementing numerical physical-flow models in real-time applications. Mesoscale weather models used for simulating energy fluxes and pollutants are yet highly demanding in computer power and user skills, and thus their implementation in the DSS is difficult. A possible solution is to run those models off-line on powerful computer clusters for many possible scenarios and then include the simulation results in a database, as in the case of BRIDGE DSS. Advances in numerical modeling, as well as in computer power, may allow more simulation models to be embedded into DSS in the future.

5. Conclusions

Several studies have addressed urban metabolism issues but few have integrated the development of methods for the combined analysis of fluxes between a city and its environment and the implementation of numerical tools for the assessment of planning alternatives, based on environmental and socio-economic indicators. The BRIDGE project integrated bio-physical observations with socio-economic data to evaluate PAs and thus addressed and jointly examined the three components of sustainability: environmental, social and economic.

The main outcome of BRIDGE was a spatial DSS. Therefore, the GIS technology was fully exploited to integrate all datasets, to analyse the various spatial entities, to prepare the inputs for the physical flow models and the decision making algorithms, to store the results and to visualise them. A MCE method was implemented in the GIS platform on which the PAs evaluation was based, providing also the option to explore the behavior of PA in extreme future scenarios. In addition to the MCE results, a cellular automata module was also integrated in the system, as a GIS application, allowing the user to estimate the impact of each PA on future land use arrangements in the broader geographical area.

The evaluation of the performance of each PA is based on the relative importance ascribed to each objective by the end-user, facilitating the integration of public concerns into decision-making. The BRIDGE DSS enables end-users to evaluate several urban PA based on previously defined sustainability objectives and indicators, by examining how each PA modifies specific urban metabolism components (energy, water, carbon and pollutants fluxes) towards sustainability. The developed decision methodology allows evaluation of a set of different alternatives, given different planning priorities. In this way, it enables quantified estimates of the effects of different combinations of planning objectives on different alternatives, promoting informed decisions.

The tool has therefore the potential to support sustainable urban planning by informing and enhancing planning processes through the detailed quantitative assessments of environmental aspects of a pair with socio-economic considerations. Although, further development of the tool is necessary until it reaches an operational state, it has great potential in supporting planning decisions accounting for urban metabolism, even in low-income cities where sustainability is critical to the provision of basic services. In this case, it can be used to support qualitative estimations of the impact of different planning alternatives, based on assumptions on the modifications they cause to energy, water, carbon and pollutants fluxes.

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Author Contributions

Zina Mitraka is the main author of this manuscript, she is responsible for the conceptual design and actively involved in all steps of its implementation. Emmanouil Diamantakis is the developer of the BRIDGE DSS prototype. Nektarios Chrysoulakis is the BRIDGE project coordinator and actively involved in the DSS implementation. Eduardo Anselmo Castro is responsible for the decision algorithms development as well as the scenario analysis methodology. Roberto San Jose is responsible for the physical numeric modeling processes carried out. Ainhoa Gonzalez is responsible for developing the indicators list in collaboration with the CoPs, developed the methodological framework and assisted in developing the decision algorithms. Ivan Blecic carried out the work related to the cellular automata.

Conflicts of Interest

The authors declare no conflict of interest.

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