Urban metabolism and resource optimisation in the urban fabric: The BRIDGE methodology

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Abstract

Like any living system, urban communities consume material and energy inputs, process them into usable forms, and eliminate the wastes from the process. This can be seen as "metabolism" of industry, commerce, municipal operations and households. Understanding the pattern of these energy and material flows through a community's economy provides a systemic reading of the present situation for goal and objective setting and development of indicators for sustainability. At present, planning policies often reflect the logic of the market. They would better reflect a vision of urban development, in which environmental and social considerations are fully embedded in spatial planning policies at all steps of the policy cycle from problem identification and policy design through to the implementation and ex-post evaluation stages. Therefore, the widespread inclusion of sustainability objectives in urban planning from regional to site level is necessary, providing the opportunity for the incorporation of bio-physical sciences knowledge into the planning process on a routine basis. To this end, the project BRIDGE (sustainaBle uRban plannIng Decision support accountinG for urban mEtabolism) aims at bridging the gap between bio-physical sciences and urban planners and at illustrating the advantages of accounting for environmental issues on a routine basis in design decisions. BRIDGE will provide the means to quantitative estimate the various components of the urban metabolism (observation of physical flows and modelling), the means for quantitative estimate their impacts (socio-economic and environmental impact assessments and indicators), as well as the means for resource optimisation in urban fabric (support the decision making in urban planning). BRIDGE focuses on the interrelation between energy and material flows and urban structure. The methodology and the conceptual design of the BRIDGE Decision Support System are presented in this study.

1. Introduction

By 2020, approximately 80% of Europeans will be living in urban areas. The growth of cities in Europe has historically been driven by increasing urban populations. However, today, even where there is little or no population pressure, a variety of factors are still driving sprawl (EEA 2006). Like any living system, urban communities consume material and energy inputs, process them into usable forms, and eliminate the wastes from the process. This can be seen as "metabolism" of industry, commerce, municipal operations and households. Understanding the pattern of these energy and material flows through a community's economy provides a systemic reading of the present situation for goal and objective setting and development of indicators for sustainability. Urban development has to meet the main requirements for sustainability, ensuring that the rate of resource use is not greater than the rate of their regeneration and that the rate of emission is not greater than the rate at which the pollutants can be absorbed. This can be expressed in the objective of optimising the use of space, energy and materials. A central objective of sustainability is to decouple conventional resource use from economic development through technological innovation, improved efficiency and changes in individual practices (Mills 2006). While there is no clear path to

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achieving sustainability, planning strategies should be based on a combination of technological innovation, changes in behaviour and improvements in design.

Past research aimed to improve decision making process towards local sustainable development, however further applied research is needed to provide tools for a more sustainable use of energy and materials in urban planning. It has been demonstrated that although compactness is a quite important feature for sustainability, urban sprawl does not necessarily mean less sustainability than the compact urban form but can be in some cases even more sustainable (less energy consumption, pollution). The assessment of the physical outcomes of urbanization processes need to be further analysed in relation to the type of land-use relationships between different scales (Geerlings and Stead 2002).

One of the biggest challenges to sustainable development is a more responsible management of natural resources. Breaking the link between the economic growth, and the use of resources has been determined as a headline objective. The design of more environmentally efficient urban agglomerations is a prime challenge for planners. The links between socio-economic driving forces, the functioning of the urban system and its environmental performance have to be understood. To this end an Industrial Ecology perspective brings valuable insight to the process of making our communities more sustainable and provides tools for understanding the environmental impacts of a community's industry, commerce, infrastructure, and household behaviour as a whole system.

Settlement planning is a key aspect of sustainability, which requires that a settlement be linked to an appropriate, local, ecological unit from which it would draw resources. There are clear links between the micro-climate of a settlement and its potential sustainability (Mills 2006). Its opportunities for gathering energy, its need for energy conservation and its ability to dispose of airborne wastes are largely controlled by the climate it experiences. Urban surface structures, such as buildings, significantly influence the water balance, the energy balance and air quality (Chrysoulakis 2002, 2003). The sustainable settlement will require a coherent strategy that applies planning tools at the appropriate scale and ensures that actions at one scale are not counteracted at another scale. At the settlement scale, the measures of sustainability should focus on the efficiency of the urban system of which a key aspect is the flow of materials and energy.

It is known that urban scientists often note the lack of communication of new knowledge and its implications to end-users, such as planners, architects and engineers. Recently, however, increasing attention is being directed to bridge this gap. The work to be carried in the framework of the FP7 project BRIDGE (sustainaBle uRban plannIng Decision support accountinG for urban mEtabolism) aims at contributing to this direction by devising innovative planning strategies for urban planning in Europe. BRIDGE is a joint effort of 14 European Organizations focusing on incorporating sustainability aspects in urban planning processes, accounting for some well recognised relations between urban metabolism and urban structure. In this study the BRIDGE methodology is presented. Its core contribution is the development of a Decision Support System (DSS) that incorporates sustainability aspects in spatial planning processes, where different visions of the problem can be shared among different actors involved, thus arriving at a consensus over the policy priorities to be reached and the policy strategies to be implemented. BRIDGE will provide the means to quantitatively estimate the various components of the urban metabolism. Its main objectives are:

- Bridge the gap between bio-physical sciences and urban planners.
- Illustrate the economic advantages of accounting for environmental issues in urban planning.
- Provide the means to quantitatively estimate the various components of the urban metabolism.
- Provide the means to quantitatively estimate the environmental impacts of the above components.
- Provide the means to translate the above impacts to socio-economic costs.
- Support the development of planning strategies to decouple resource use and economic development.
- Provide the means to optimise resources in urban planning.
- Involve local and regional stakeholders in validation of project’s achievements.
- Support the implementation of EU policy on urban environment.

2. Methodology

Four sectors are regarded as important for urban development: urban structure, transportation, energy and material flows, socio-economy. BRIDGE focuses on the interrelation between energy and material flows and urban structure. Transport is the sector interrelated strongest to the urban patterns (Steemers 2003) and thus the BRIDGE objectives are also closely linked. The analysis carried out in BRIDGE addresses the different scales allowing different levels of institutions to benefit from its outcome, contributing to sustainable use of energy and materials from regional to site level. In order to develop a method that will be welcomed by local governments, it is important to involve them in the project from the beginning. The project uses a Community of Practice (CoP) approach, which means that in specific case studies, local stakeholders and scientists of the BRIDGE project will meet on a regular basis in order to learn from each other. The CoP will make clear what aspects are important for the future users of the BRIDGE products.

BRIDGE is characterized by multidisciplinary research: the role of land use in relation to urban pattern and typology will be assessed using remote sensing (Chrysoulakis et al. 2004). The flows of energy and material between the urban system and its environment will be measured and modelled using recent advances in urban climatology (Grimmond 2006, Souch and Grimmond 2006). The exchanges of moisture, carbon dioxide, radiation, heat, momentum, and other quantities will be described by advanced model parameterisation of turbulence, plant physiology, soil and surface physics, and radiation transfer (Pyles et al. 2003). The observational data will be used to validate the different mathematical procedures to assure that the different methods and interactions are reflecting the reality. Environmental impact of the above flows will be evaluated based on recent advances of environmental science, whereas state of the art methodologies will be used to evaluate their socio-economic costs (Donelly et al. 2006, 2007). Finally, Geographical Information Systems (GIS) capabilities will be exploited to develop a DSS capable of integrating the data, the model results and/or the models and the impact assessment methodologies and of providing scenarios for resource optimisation in urban fabric. These scenarios will be evaluated by end users in BRIDGE study areas, contributing to the development of new strategies for a more sustainable use of energy and materials in urban planning. The DSS stem will be demonstrated and its European applicability will be examined. During the lifetime of the project the CoP's will generate a continuous exchange of ideas and experiences between stakeholders and scientists which will ensure feedback of end-users and scientist of other disciplines at all stages of the project.

In BRIDGE, the 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: a) energy; b) water; c) carbon and pollutants. Due to the large heat capacity of water and the energy released by evaporation, there is a strong link between the energy and water balance of an urban area. Therefore the energy and water fluxes will be measured and modelled in order to define the spatio-temporal distribution of energy and water balance (Offerle et al. 2006, Masson 2006, Mitchell et al. 2007). Moreover, the fluxes of carbon and pollutants will be modelled and their spatio-temporal distributions will be estimated (Borrego et al. 2006). The uptake by trees and onward transport or storage of various pollutants in the urban environment can be measured by a range of techniques and can also be modelled to some extent. The urban metabolism problems related to energy and material flows can be simulated in a three dimensional 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.

Based on the quantitative estimations of energy and material flows, a set of environmental and socio-economic impacts can then be defined. The DPSIR (Driving Force-Pressures-State-Impact-Response) framework defined by the European Environmental Agency (http://www.eea.europa.eu) is a very useful conceptual tool to define in an easy to understand manner the cause-effects relationships at stake. The

NetSyMod (Network Analysis - Creative System Modelling - Decision Support) participatory methodology (http://www.netsymod.eu) will be used to provide valuable inputs, as it allows different visions of the problem to be shared among the different actors (e.g. local and regional Authorities, urban planners, infrastructure developers, social networks and citizens, scientific community), arriving at a consensus over the main components of the urban socio-economic and environmental systems. Once the impacts have been agreed upon, it is necessary to select relevant indicators capable of assessing them in a quantitative way in each of the study areas (Donelly et al. 2006, 2007). Once the list of impact indicators has been defined, each indicator's performance will be assessed with respect to the objectives of sustainable urban planning stated above. Impact indicators will be also used to assess different planning scenarios, as input into the DSS through, for instance, their integration in a Multi Criteria Analysis (MCA) framework that enables comparing and aggregating across several dimensions.

The core of the BRIDGE project is the DSS, a computer based information system that assists decision making processes by providing tools for the design and a structured presentation of alternatives and mechanisms for the comparative analysis, ranking, and selection (Carsjens and Ligtenberg 2007). Decision making means selecting between alternatives. The main function of a DSS is therefore to present, or design and generate alternatives, and provide the tools for their selection, given the decision makers objectives, criteria, and constraints (Fedra 2000). The scenario analysis technique is used and alternatives are evaluated and compared addressing "what if" questions. Scenario analysis starts with a set of control settings or decisions, and estimates their consequences. The descriptive approach of scenario analysis leads, in the next step, to prescriptive approaches based on some concept of optimisation. Here the "what if" questions of scenario analysis are reformulated as "how to": The desired outcome is given, and the control setting or decision necessary to reach these goals, are sought. The observations of physical flows, the models and/or the models results, the environmental impact assessment methodologies and the scocio-economic costs assessments methodologies will be integrated in the DSS and scenarios will be provided for resource optimisation in the urban fabric.

The understanding of the complex relationships between the drivers of urban phenomena, their impacts and society's responses to them will therefore be facilitated, and the causal links between the different interacting components of social, economic and environmental issues involved by urban metabolism established. As changes of the state will be traced, impacts will be assessed and evaluated, and potential policy responses identified and compared within a DSS approach. BRIDGE will therefore address this methodological concern by taking advantage of participatory approaches for stakeholders' involvement. One of the main purposes of the CoP is to acknowledge into the DSS development the different stakeholders' perceptions. The end users are strongly involved in urban planning, since most of them work in city planning organizations in BRIDGE study areas. Urban planners in these organizations, who are aware of human reactions and behaviours in reply to urban planning policies, will provide their requirements for the DSS development they will evaluate the DSS prototype and collaborate on the surveys supporting future scenario analysis and selection.

Five European cities have been selected as case studies: a high latitude with rapid urbanization city that requires a substantial amount of energy for heating (Helsinki, Finland); a low latitude Mediterranean city that requires a substantial amount of energy for cooling (Athens, Greece); a representative European mega-city (London, United Kingdom); a representative European old city with substantial cultural heritage (Firenze, Italy) and a representative Eastern European city with dynamic planning process reflecting the economical, social, and political changes held within last two decades (Gliwice, Poland). The overall BRIDGE approach is shown in Figure 1. Not shown in the figure is the cross cutting process of the CoP's, which facilitates the continuous interaction with the end-users. BRIDGE will support the decoupling of the resource use from economic development by devising innovative strategies to optimise urban planning in order to reduce space and resources consumption, as well as to sustainable use of energy and materials in the urban fabric. These strategies will be based on land use planning scenarios devised by the DSS. The environmental and socio-economic impacts of urban metabolism will be taken into account in these scenarios. The impacts of urban metabolism will be assessed by quantitative estimating the relevant physical flows (energy, water, carbon and pollutants). State-of the art observation methodologies and models will be used to identify the spatio-temporal distribution of each flow and to assess its behaviour in the urban fabric. State-of the art impact assessment methodologies and indicators will be used to assess the environmental and socio-economic impacts of these flows addressing the economic, institutional and regulatory factors. Impacts will be assessed from regional to site level using appropriate downscaling methods. Consequently, the DSS will integrate the observational data, the models and/or the models results and the impact assessment methodologies in order to device planning scenarios in which the use of energy and material will be optimised from the environmental and socio-economic point of view.

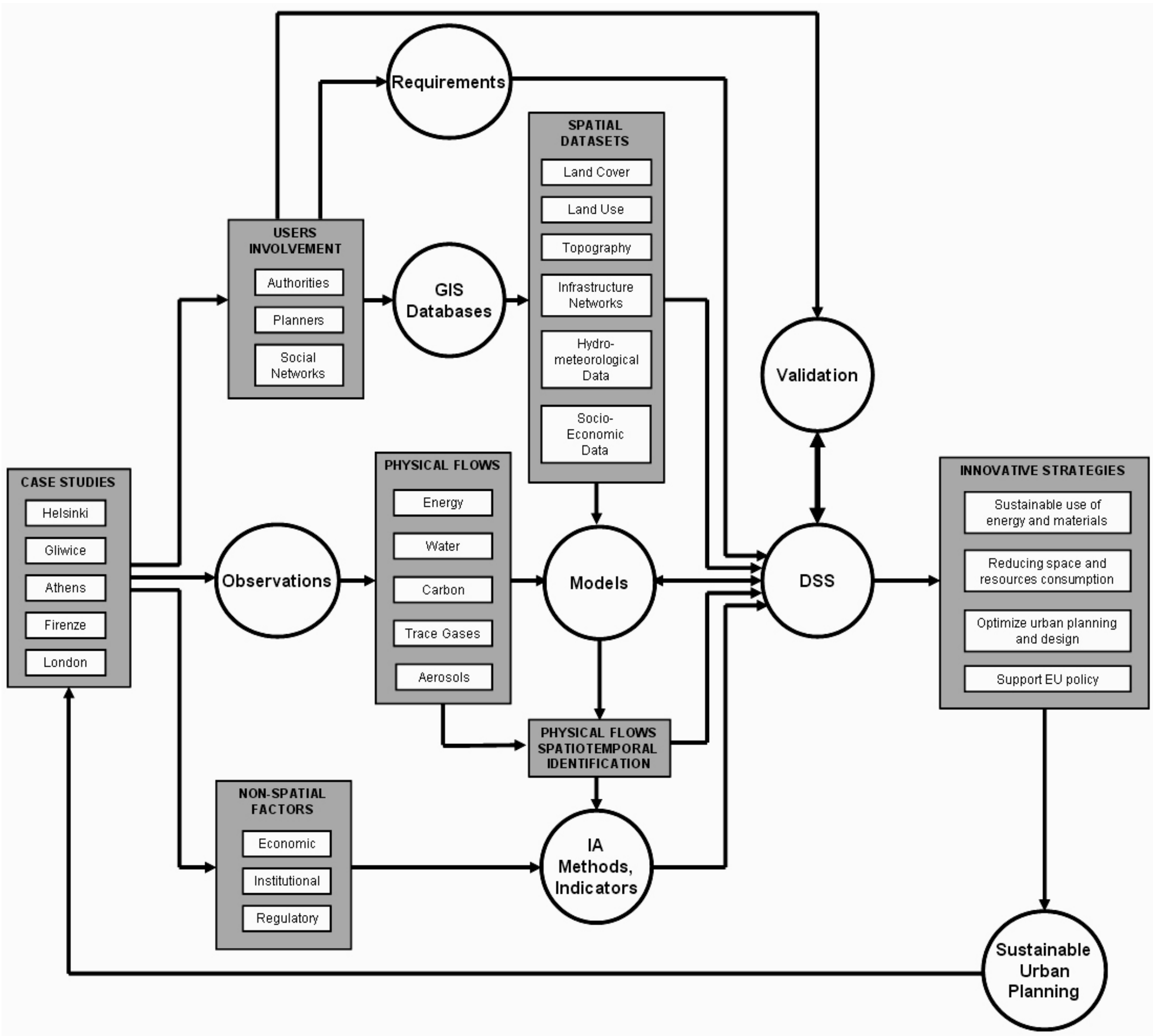

Figure 1. The BRIDGE methodology.

3. Implementation

A conceptual illustration of the BRIDGE DSS is shown in Figure 2. It offers an analytical (i.e. the one that supports the assessment of the environmental implications of resource use and land-use arrangement), as well as a design (i.e. the one that allows for making hypotheses in terms of planning decisions) component. A module based on MCA and a module based on the Cellular Automata (CA) paradigm (Cecchini 1996, Barredo et al. 2003) will be also integrated in the DSS. The CA module will enable to make probabilistic predictions about the fate of individual parcels of urban land based on their individual characteristics, as well as on the type of urban functions in their neighbourhoods. Both MCA and CA modules will have the role of a middleware between the two DSS components. More specifically, the environmental and socio-economic impacts of urban metabolism for a given urban structure and a given level of resource use (BRIDGE case studies) will be addressed using the analytical component. This component will have four major functions for analysing energy, water, carbon and pollutants flows and assessing the respective environmental impacts. These impacts will be following translated into socio-economic costs. The design component will be used to provide modified land use arrangements and alternative practices for resource use based on sustainable planning scenarios. It will therefore provide quantitative assessments of the environmental benefits of reducing air pollution, slowing storm water runoff and conserving energy. Moreover it will translate these environmental benefits 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 DSS will be internally able to model how planning strategies, together with all relevant external forces and events, may influence over time some significant features, such as the spatial distribution of urban functions and the kind and the amount of urban land uses. The DSS will be composed of the following modules:

- The GIS that is used to integrate all datasets, analyse the various spatial entities, prepare the data for the models, store the results and then visualize them.
- The CA and MCA modules which will have the role of the middleware.
- The 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.
- The impact assessment methodologies for evaluating the environmental and socio-economic impacts.
- The decision rules which compare the impact on the basis of some criteria and can assist decision makers on the preferred actions to be taken.
- The Graphical User Interface, which integrates all other components in one integrated system and hides the intricacies of the system for the user.

The spatial entities will be stored in the GIS, however, the various attributes associated with each spatial object will be stored in a Database Management System. The data flow between the “on-line” models and the databases will be handled through interfaces which will be developed, namely “model encoding” and “model decoding” components. A “model encoding” component will read the geographic and attribute databases and prepare the input files needed for running a specific model. A “model decoding” component will have the role to translate these files into a standard structure that can be handled by any the GIS.

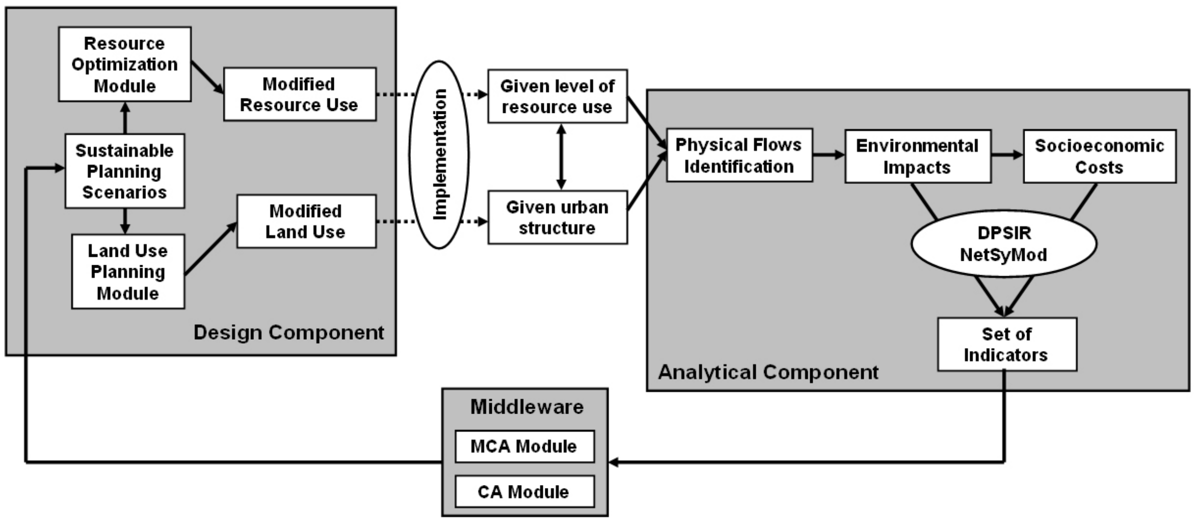

Figure 2. Conceptual illustration of the BRIDGE DSS.

The DSS will be validated by end users in BRIDGE case studies who will provide their requirements during its design phase. The DSS will be developed in an iterative procedure with two main phases. User requirements will lead to the specifications for the DSS design. DSS design will lead to the development of the First DSS Prototype. Users will evaluate it and their evaluation results will lead to specifications for the Final DSS Prototype, which will be validated in each case study. The iterative process to optimise the DSS development will be further strengthened using continuous input of observational data. As it has been already mentioned, the DSS will be used to device planning scenarios which will result in reducing of waste and saving raw materials without harming the economic development and social welfare. In this way the implementation of EU related policy (Thematic Strategies on urban environment, sustainable use of resources and prevention and recycling of waste) will be supported.

The evaluation of methods, models and DSS presupposes the definition of a set of strategic scenarios based on environmental and socio-economic indicators for baseline and extreme situations. In this scope, a number of key issues will be addressed in the definition of strategies for future urban development under environmental and political constraints such as: a) climate change impacts and adaptation; b) mobility; c) energy and renewable sources; d) land use change and territorial boundaries. The more the stakeholders related to urban processes are involved in decision-making, the more knowledge will be accumulated and the easier it will be to avoid possible conflicts by identifying them and channelling them towards more constructive ends. The DSS will make it possible to evaluate site plans and development scenarios in order to set planning strategies and to determine sustainable practices. With its assistance, BRIDGE anticipates urban planning policy recommendations for localities with respect to integrating a sustainable development approach to their infrastructure planning. Consequently the DSS will allow urban planners to calculate the economic benefits provided by sustainable planning scenarios, supporting in this way decoupling of resource use from economic development.

4. Conclusions

The innovation of BRIDGE lies in the development of a DSS which reflects the multidimensionality nature of the urban metabolism, as operationalised in intelligible and transferable indicators easily understood by a non-scientific public. The development of this 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 impacts and the socio-economic costs of urban metabolism components. The decoupling of resource use from economic development will be supported by quantitative estimating the economic benefits provided by taking into account urban metabolism in urban planning. The bio-physical processes is linked to socio-economic parameters in the DSS by means of a group of multivariate analysis techniques, principal component analysis and cluster analysis; econometric - multi criteria analysis and cellular automata. The DSS will be developed in a GIS environment integrating the above methods with bio-physical observations, socio-economic data and models. The DSS will provide several urban planning scenarios, which will be evaluated by the end users. In this way sustainable planning strategies will be proposed based on quantitative assessments of urban metabolism components.

Several studies have addressed urban metabolism issues, but few integrated the development of numerical tools and methodologies for the analysis of fluxes between the 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. BRIDGE will advance the state of the art as it will provide the means to integrate information on physical fluxes of natural resources, energy and material with social and economic changes and policy priorities. More specifically, the advance that the project will bring about is related to: instrumentation, databases, modelling, DSS and sustainable planning strategies. The evaluation of project progress and performance of will be made through publications, benchmarking, completion rates and inter-comparison with other systems and methodologies. The overall performance indicator will be the extent to which EU and national planning authorities and urban planners are involved in and then make use of BRIDGE outputs.

Bibliography

Barredo J.I., Kasanko M., McCormick N., Lavalle C. (2003): Modelling dynamic spatial processes: simulation of urban future scenarios through cellular automata. Landscape Urban Plan., 64: 145 - 160.

Borrego, C., Martins, H., Tchepel, O., Salmin, L., Monteiro, A. and Miranda, A.I. (2006): How urban structure can affect city sustainability from an air quality perspective. Environ. Modell. Softw., 21: 461 - 467.

Carsjens, G. J., and Ligtenberg, A. (2007): A GIS-based support tool for sustainable spatial planning in metropolitan areas. Landscape Urban Plan., 80: 72 - 83.

Cecchini A. (1996): Urban Modelling by means of cellular automata: generalised urban automata con the help on-line (AUGH) model. Environment & Planning B: Planning and Design, 23: 721 - 732

Chrysoulakis, N., Kamarianakis, Y., Farsari, Y., Diamandakis, M. and Prastacos, P. (2004): Combining satellite and socioeconomic data for Land Use Models estimation. In: Goossens, R. (Editor), Proc. Of 3rd Workshop of EARSeL Special Interest Group on Remote Sensing for Developing Countries.

Chrysoulakis, N. (2003): Estimation of the all-wave Net Radiation Balance in Urban Environment with the combined use of Terra/ASTER multispectral imagery and in-situ spatial data. J. Geophys. Res., 108: D18, 4582.

Chrysoulakis, N. (2002): Energy in the Urban Environment: Use of Terra/ASTER imagery as a tool in Urban Planning. J. Indian Soc. Rem. Sens., 30: 245 - 254.

Donnelly, A., Jones, M. B., O'Mahony, T. and Byrne, G. (2007): Selecting environmental indicators for use in strategic environmental assessment. Environ. Impact Assess. Rev., 27: 161-175.

Donnelly, A., Jones, M.B., O'Mahony, T. and Byrne, G. (2006): Decision support framework for establishing objectives, targets and indicators for use in SEA. Impact Assessment and Project Appraisal, 24: 151 - 157.

EEA, (2006): Urban sprawl in Europe — the ignored challenge, EEA Report No 10/2006, European Environment Agency, Copenhagen.

Fedra, K. (2000): Environmental Information and Decision Support Systems. Informatik, 4: 14 - 20.

Geerlings, H. and Stead, D. (2002): Integrating Transport, Land-Use Planning and Environment Policy in European Countries. EJTIR, 2, 215 - 232.

Grimmond, C.S.B. (2006): Progress in measuring and observing the urban atmosphere. Theor. Appl. Climatol., 84: 3 - 22.

Masson, V. (2006): Urban surface modelling and the meso-scale impact of cities. Theor. Appl. Climatol, 84: 35 - 45.

Mills, G. (2006): Progress toward sustainable settlements: a role for urban climatology. Theor. Appl. Climatol., 84: 69 - 76.

Mitchell, V. G., Cleugh, H. A., Grimmond, C. S. B. and Xu, J. (2007): Linking urban water balance and energy balance models to analyse urban design options. Hydrol. Process., DOI: 10.1002/hyp.6868.

Offerle B., Grimmond, C. S. B., Fortuniak, K. and Pawlak, W. (2006): Intra-urban differences of surface energy fluxes in a central European city. J. Appl. Meteorol., 45: 125 - 136.

Pyles, R.D., Weare, B.C., Paw U, K.T., Gustafson, W. (2003): Coupling between the University of California, Davis, ACASA and MM5: Preliminary Res. July 1998 for Western North America. J. Appl. Meteorol. 42: 557 - 569.

Souch, S. and Grimmond, S. (2006): Applied climatology: urban climate. Prog. Phys. Geog., 30: 270- 279.

Steemers, K. (2003): Energy and the city: density, buldings and transport. Energ. Buildings, 35: 3 - 14.