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ICT for Urban Metabolism: The case of BRIDGE

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Abstract

Cities consume material and energy inputs, process them into usable forms, and eliminate the wastes from the internal processes. These processes comprise the "metabolism" of industry, commerce, municipal operations and households. A bottom-up approach based on quantitative estimates of urban metabolism components, at local and regional scales, can be obtained by considering the three-dimensional (3D) exchange and transformation of energy and matter between a city and its surroundings. Recent advances in bio-physical sciences have led to new methods and models to estimate local scale flows. However, there is often poor communication of new knowledge and its implications to urban planners, architects and engineers. Recently, increasing attention is being directed to bridge this gap. One opportunity of Information and Communication Technology (ICT) to reduce this gap is through better integration of scientists into planning. Here, ICT tools and techniques that can be used in bottom-up urban metabolism studies, focusing on energy, water, carbon and pollutants are briefly reviewed. How these tools and techniques are used in the BRIDGE project to develop a decision support system to address the challenges of sustainable urban planning with regards to the urban metabolism is outlined. The approach proposed provides quantitative measures of energy, water, carbon and pollutants fluxes, estimates their environmental impacts and socioeconomic benefits and proposes guidelines for resource optimisation.

1. Introduction

Urban metabolism (Wolman 1965) considers a city as a system and usually distinguishes between energy and material flows as its components. "Metabolic" studies are usually top-down approaches that assess the inputs and outputs of food, water, energy, and pollutants from a city (Ngo and Pataki 2008), or that compare the changing metabolic process of several cities (Kennedy et al. 2007). In contrast, bottom-up approaches are based on quantitative estimates of urban metabolism components at local to regional scales. Such approaches consider the urban metabolism as the 3D exchange and transformation of energy and matter between a city and its environment. Again, the city is considered as a system, but the physical flows between this system and its environment are quantitatively estimated. In this case, the potential of ICT (Information and Communication Technology) is high, since ICT methods and tools (sensors, models, geo-spatial analysis tools, etc.) can be used to represent the dynamics of the physical system, as well as to evaluate how planning alternatives can modify the physical flows of urban metabolism components.

The transformation of landscapes from primarily agricultural and forest uses to urbanized landscapes can greatly modify energy and material exchanges and it is, therefore, an important aspect of an urban area. Here we focus on the exchanges and transformation of energy, water, carbon and pollutants.

Energy is almost everywhere, in different forms that can be transported, stored and transformed. Electricity, heat, radiation, fuels, materials, evaporation, emissions and some of the material flows (e.g. water flow) also involve exchanges of energy. Ecologists often attempt to integrate the energy which is contained in material, energy and information flows into a consistent measurement scheme using the concept of "embodied energy". Embodied energy (or "emergy"), can provide a single measurement that accounts for all the flows associated with urban material metabolism and between this metabolism and its surroundings (Zhang et al. 2009). Decker et al. (2000) distinguished flows of energy and matter in urban metabolisms into active inputs (e.g. human work) and passive inputs (e.g. solar radiation). Energy enters, passes and leaves the system in several ways and in several physical states and forms. Fuels (like coal, oil and natural gas), electricity (generated from different sources), radiation and heat are the main categories. However, construction materials, food, water and waste also have stored energy. The aspects of energy which are of interest depend on the point of view: urban planners, city administrations, economists and statisticians often have a different focus to natural scientists such as meteorologists or physicists. The former have to deal primarily with fluxes of "usable energy", the optimisation of use and questions such as how energy consumption can be influenced by administrative means, for example, guidelines for insulation of new houses, old-building renovation, traffic reduction etc. The latter are more interested in understanding how energy in the form of radiation and heat influences the urban climate and how it is transported and stored (e.g. in urban built structures). Within each of the approaches, the perspective of the other normally is included only marginally. If there is overlap, for a single planning approach or within a certain study, the other parts are generally summarized to one single factor in the system considered. Energy flow charts by urban planners usually omit radiation as a heating source and the anthropogenic heat contribution to emitted radiation, as well as in the atmospheric heat fluxes are part of those fluxes that are summarized as losses from the system. From the micrometeorological point of view, those losses are one input factor to the urban energy balance, considered in terms of the anthropogenic heat flux (Roberts et al. 2006).

The recent focus on urban sustainability and the potential effects of climate change have led to a large number of Urban Water Balance (UWB) studies that emphasize water sustainability and management techniques (Wolf et al. 2007, Haase 2009). Traditional urban water systems are often considered non-sustainable due to the supply of high quality treated water for all processes (i.e. residential, industrial and irrigation) and the reliance on and minimal reuse of water for the transport of waste, which typically is treated before being returned to natural water courses (Wilderer 2004). In addition, the transport and removal of water through the piped water system adds an anthropogenic component to the cycle. Artificial surfaces found in urban areas enhance the surface runoff leading to an enhanced risk of flooding and the transport of pollutants (Burian et al. 2002), along with a reduction in infiltration leading to lower replenishment of groundwater (Stephenson 1994). Therefore, new methods are required to improve the level of sustainability through improved water management both at and away from the point of demand. Such schemes include the reuse/recycling of treated wastewater for non-drinking applications (e.g. irrigation), rainwater capture and toilet flushing and washing (Mitchell et al. 2001, Ragab et al. 2003, Xiao et al. 2007). Additionally, the separation of solid waste using septic systems could reduce water use in the removal of sewage (Wilderer 2004). An urban hydrological framework is required to asses the effectiveness of the new methods. The UWB is a framework that can be utilized to assess the implications of applying sustainable urban water practices. The UWB applies the principle of mass conservation to the transfer of water through a specific domain or catchment, allowing the study of both spatial and temporal patterns of water usage (Mitchell et al. 2001). The UWB framework aims to provide an estimate of urban hydrologic processes that are intrinsically different to those observed in rural areas due to differences in land surface properties and the presence of artificial piped networks (Haase 2009). The UWB is directly linked to the surface energy balance as the mass of evapotranspiration is equivalent to the energy term for latent heat flux (Grimmond and Oke 1991).

Most attempts to quantify the role of urban areas on carbon budgets have focused largely on inventories of emissions. In these studies, fossil fuel consumption, cement production, etc. have been estimated, along with the amount of carbon sequestered in urban vegetation based on biomass estimates (Johnson and Gerhold 2003). For urban ecosystems, few data are available to assess whether urbanization leads to modifications of components of carbon exchanges such as an increase or decrease in soil carbon pools.

Pollutants also play an important role in urban ecosystems. Most natural releases are essential for the maintenance of life, but they are classified pollutants when their concentration is too high. In urban areas, concentrations of atmospheric pollutants are controlled by the balance between those factors which lead to pollutant sources and sinks. Emission and dispersion processes are influenced by a wide range of factors at different temporal and spatial scales. The nature of emissions and the state of the atmosphere determine the amount of pollution at a site. The amount and type of pollutant are controlled by the rate of emission, physical and chemical nature of the pollutants, the morphology of the emission area, the duration and the timing of the releases and the location of pollutant release. Despite major technical advances in engine technology, exhaust filtering and fuel composition (that affects the emissions of CO_2 and pollutants), traffic remains one of the major sources for contamination in urban areas.

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

- Energy: optimise energy efficiency of the urban structure; minimise energy demand of settlements; maximise efficient use of energy through building services and energy supply; maximise share of renewable energy sources; maximise the use of eco-friendly and healthy building materials.
- Water: minimise primary water consumption; minimise impairment of the natural water cycle.
- Carbon and pollutants: minimise the emissions to the atmosphere; maximize pollutant sinks.

To address these challenges, information on the distribution and flows of energy, water, carbon and pollutants in urban systems is needed. The energy flow within a city is primarily dictated by internal activities, such as industrial, level of socio-economic development and building style/intensity. The energy flow is related to CO_2 and pollutants production and it depends on the prevailing weather and its structure. Urban microclimate is controlled by the arrangement of roads, buildings and vegetation. The growth of urban population increases the demand for resources such as water and the infrastructure. Added to this is the uncertainty and potential impacts due to climate change.

Recent advances in bio-physical sciences have led to new methods and models to estimate local scale energy, water, carbon and pollutants fluxes. However, there is if often poor communication of new knowledge and its implications to end-users, such as planners, architects and engineers. Recently, there has been increasing attention to bridge this gap (Chrysoulakis 2008), and ICT can help through better integration of scientists into planning.

In Section 2, methods and tools for use in bottom-up urban metabolism studies are reviewed. Section 3 shows how these tools are used for the development of a Decision Support System (DSS) in the framework of the FP7 Project BRIDGE (SustainaBle uRban plannIng Decision support accountinG for urban mEtabolism) and how this DSS can be used to evaluate planning alternatives.

2. Methods and tools for bottom-up urban metabolism studies

2.1 Sensors and models for energy, water, carbon and pollutants fluxes

Energy, water and carbon fluxes in urban areas are investigated in contemporary studies by three main approaches of natural science: micrometeorological site studies, remote sensing measurements and numerical modelling approaches. Each approach has its advantages but also restrictions and methodological imperfections. Micrometeorological methods are mainly based on eddy covariance techniques which use high frequency instruments such as ultrasonic anemometer-thermometers coupled with open or closed path infrared gas analysers. Remote sensing methods, which are described in the next section, have also advantages and disadvantages. If properly developed and tested using micrometeorological and remote sensing measurements, modelling offers an opportunity to simulate and study potential changes of the urban system. An extensive urban surface energy balance model comparison to evaluate the different schemes is being carried out by Grimmond et al. (2009).

In terms of water fluxes, new sensors, for example sensitive pans to measure precipitation have been deployed in urban areas as an alternative to traditional raingauges (Basara et al. 2009). Radar can provide spatial information but cannot be used alone due to uncertainty in its accuracy (Vieux and Bedient 2004). The magnitude of the water supplied is driven by a combination of demand from urban inhabitants and supply by the water utility companies. This is limited by availability of surface and groundwater supplies. Measurement of the supplied water is often provided by water utility companies (Morris et al. 2007). However, internal residential/industrial water usage is difficult to quantify accurately as it is based on a large number of human decisions. Determining the amount of external irrigation is a much more complex problem as it is related to the human perception and behaviour (Arnfield 2003). Further anthropogenic water sources include the release of moisture from air conditioning, heating/cooling applications, the moisture released from industry, the moisture released due to combustion from vehicles and the consumption of bottled water used for drinking and cooking before eventually being released into the waste water system. At the local scale micrometeorological techniques can be used to determine evapotranspiration: Direct measurement of the latent heat flux use eddy covariance methods through high frequency measurement of the vertical velocity with a sonic anemometer and specific humidity using a gas analyzer such a Krypton hygrometer, Lyman-alpha, infrared gas analyser (Grimmond 2006).

Runoff measurements include the use of flow meters to determine discharge through the drainage network, soil moisture measurement to determine soil water content, runoff capture techniques for smaller study catchments and runoff flow measurement techniques on the boundaries of the study area. Runoff for larger urban catchments can be modelled using dedicated hydrology models (Rodriguez et al. 2008). One of the main stores of water within a study area is the groundwater within the soil and deeper aquifer. Techniques for measuring groundwater and soil water storage include tensionmeters (for soil water potential) and time domain reflectometry (for volumetric soil water content), borehole measurement and gravimetric sampling (for soil water content) (Grimmond and Oke 1986).

The accurate representation of the UWB through modelling is imperative for the assessment of future sustainable urban water management practices, realistic simulation of urban surface processes and for predicting the effects of climate change. A review of the literature identified three general types of UWB models each with varying degrees of complexity and spatial extent: mass balance based approaches (Mitchell et al. 2001, Diaper and Mitchell 2007); urban parameterisation schemes used in global and mesoscale numerical weather models (Berthier et al. 2004, Lemonsu et al. 2007); and hydrological models (Jia et al. 2001, Rodriguez et al. 2008, Wang et al. 2008).

Surface-atmosphere carbon and pollution fluxes are commonly measured using several methods:

- Enclosure techniques measure changes in mean concentration within a representative sample of a surface.
- Budget techniques extend enclosure principles to a volume of the atmosphere.
- Chemical methods for measuring the CO_2 content of air.
- The non-depressive infrared CO_2 analyser (Tanaka et al. 1983), and laser photo-acoustic spectrometry (Sigrist 1994) can be used for experimental CO_2 and trace gas measurements.
- Micrometeorological techniques (Baldocchi et al. 2001a,b).
- Emission inventories validated with air quality data.

Vertical carbon fluxes can be estimated using ecosystem process models (Bandaranayake et al. 2003, Qian et al. 2003, Milesi et al. 2005). The ecosystem process models are able to estimate vertical carbon fluxes of vegetation and soils with detailed representation of ecosystem processes. To address the specific problems of regional pollution and waste management, an approach was developed modeling urban biogeochemical fluxes (Bower 1977, Brunner et al. 1994). Carbon fluxes related to human activities can be estimated using models developed in industrial ecology, following the urban metabolism concept. Examples are reported by Ayres and Ayres (2002). Modelling the transport and dispersion of pollutants in the urban area has been the subject of much recent effort. Several models were used to predict pollutants concentration and distribution in urban areas. These include semi-empirical models, stochastic models (Mammarella et al. 2009), mechanistic models (Kleeman and Cass 1998), chemical mass balance receptor models (Zheng et al. 2005), chemical transport models (Hodzic et al. 2004, Borrego et al. 2003, San Jose et al. 2008, Zhang et al. 2009), computational fluid dynamics models (Milliez and Carissimo 2007) and probabilistic models (Yee and Wang 2009).

2.2 Remote sensing and GIS

Remote sensing and Geographical Information Systems (GIS) provide data and analytical tools for the study of urban environments. GIS are used in spatial (environmental and socioeconomic) data analysis and management, to explain observations and to provide the key parameters for urban models and spatial DSS development. The role of Earth Observation in sustainable urban planning and management has been described in detail by Nichol et al. (2007) focusing on how the role of land use in relation to urban pattern, typology and surface characteristics can be assessed. Beyond these well known applications, remote sensing can be used is often used to assess the surface radiation balance, the surface temperature and characteristics, the precipitation and the air quality (mainly urban aerosols). Thermal remote sensors provide spatial patterns of upwelling thermal radiance, as a function of view angle, urban morphology, pixel size, spectral response of the remote sensor etc. (Roth et al. 1989, Gallo et al. 1995, Streutker, 2002, Voogt and Oke 2003, Dousset and Gourmelon 2003, Kato and Yamaguchi 2005, Stathopoulou and Cartalis 2007). Satellite measurement of rainfall using radar such as the Tropical Rainfall Measuring Mission (TRMM) is another method to observe rainfall (Kamarianakis et al. 2008). Finally, there is a relatively long history of the quantitative estimation of aerosol optical depth from remotely sensed data using multiangular information (North 2002), polarization information (Deuze et al. 2001), multispectral information (Kaufman et al. 1997, Liang and Fang 2004, Liang et al. 1997) and multitemporal information (Christopher et al. 2002).

2.3 Decision Support Systems (DSS)

A DSS is an information system that assists decision making processes by providing tools, often computer based, for presentation of alternatives for comparative analysis, ranking, and selection (Carsjens and Ligtenberg 2007). Numerous disciplinary areas are relevant to DSS development. ICT provides data, database design models, simulation models and programming support tools. Management science and operations research provide the theoretical framework of decision analysis for the design of useful approaches to making choice. Organizational behaviour, behavioural, and cognitive science provide information concerning how humans and organizations process information and make judgments in a descriptive fashion. The structure and components of DSS are linked to the specific problem addressed and the characteristics of the actor(s) involved. The most important processes that are supported by DSS, include (Böhner 2006):

- 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.
- Guiding generation of possible alternative solutions to the problem.
- Modelling and simulation of impacts deriving from desired, proposed or existing alternatives.
- Comparison of the performance of each alternative solution considered with a set of decision criteria and preferences formulated by the decision maker.
- Analysis and evaluation of possible conflicts deriving from the different sets of preferences linked to different actors within the process of decision making.

In practice, the problem is that some options may be good according to some criteria whereas other options will do better against differing criteria. Choosing one of the alternatives over the others means that the priorities must have been set in such a way that accomplishing some goals would sacrifice others. The objectives are usually conflicting and, therefore, the solution is a trade-off between a number of objectives which in turn depend on the preferences of the decision-makers. To overcome these problems, the Multi Criteria Decision Making (MCDM) technique can be used, since it provides solutions to the problems involving conflicting and multiple objectives. Several methods based on weighted averages, priority setting, outranking, fuzzy principles and their combinations are employed for urban planning decisions. A review of the application of MCDM to sustainable energy planning was given by Pohekar and Ramachandran (2004). A framework of the MCDM method has two main phases.

- Phase I: the users decide on the objectives to cover their needs and determine their relative importance. Since there are many objectives to consider, it is suggested to organize them into a limited number of main objectives; each having several criteria. In this phase, the scales can also be established that will be used later in scoring the various criteria.
- Phase II: MCDM is used to judge the relative merits of the alternatives. This is done by determining scores for each alternative for each objective, using the measuring scales defined in the first phase. The scores can be aggregated into several overview presentations.

A DSS for urban planners based on the bottom-up urban metabolism approach can be developed if ICT provide the tools and techniques to exploit the recent advances in bio-physical sciences. Such a DSS should have the potential to support the decision making needed to address the challenges of the sustainable urban planning with regards to the urban metabolism, by providing quantitative measures of energy, water, carbon and pollutants fluxes and by estimating their environmental/socioeconomic impacts.

3. Implementation in the framework of BRIDGE

The FP7 project BRIDGE aims at bridging the gap between bio-physical sciences and urban planners and 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 it will rather provide the means to generate quantitative estimates of specific components of the urban metabolism (observation and modelling of fluxes of energy, water, carbon and pollutants), the means to quantify their impacts (socio-economic and environmental impact assessments and indicators), as well as the means for resource optimisation in the urban fabric (support the decision making in urban planning). BRIDGE therefore follows the bottom-up approach to urban metabolism focusing on the fluxes of energy, water, carbon and pollutants (Chrysoulakis 2008).

3.1 The involvement of users

Five European cities have been selected as case studies: a high latitude city with rapid urbanization that requires a substantial amount of energy for heating (Helsinki); a low latitude Mediterranean city that requires a substantial amount of energy for cooling (Athens); a representative European mega-city (London); a representative European old city with substantial cultural heritage (Firenze) and a representative Eastern European city with dynamic planning process reflecting the economical, social, and political changes that occurred within last two decades (Gliwice). The project uses a “Community of Practice” approach (Groot et al. 2009), which means that local stakeholders and scientists of the BRIDGE project meet on a regular basis in order to learn from each other. This approach will make clear what aspects are important for the future users of the BRIDGE products.

3.2 The physical flows observations and modelling

The energy and water fluxes are measured and modelled in order to define the spatio-temporal distribution of the energy and water balance at local scale (Offerle et al. 2006, Masson 2006, Mitchell et al. 2007). The fluxes of carbon and pollutants are modelled and their spatio-temporal distributions are estimated (Borrego et al. 2006). The uptake by trees and onward transport or storage of various pollutants in the urban environment are measured by a range of techniques (Freer-Smith and Taylor 2001) and can also be modelled to some extent. These fluxes 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 (San Jose et al. 2008).

3.3 The impact assessment methods

The urban metabolism is analysed in terms of inputs and outputs of energy, water, carbon and pollutants to and from the urban system. The system inputs relate to human needs or resource demands (i.e. drivers). The outputs include the transformation of input resources into heat, waste water and pollutants (i.e. local-scale impacts). This analysis will take account of sustainability objectives and criteria (i.e. targets). The exchanges and transformations in an urban system and the effectiveness of the implementation of those sustainability objectives will be monitored through the measurement of indicators. BRIDGE will therefore employ tools for the integration of key environmental and socio-economic considerations into urban planning through Strategic Environmental Assessment (Donnelly et al. 2006).

3.4 The BRIDGE DSS

The innovation of BRIDGE mainly 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 urban planners. A MCDM has been adopted in BRIDGE DSS. This method is conducted in a user-friendly seven-step procedure: a) selecting the main goals the objectives and the criteria; b) developing measurement scales for the criteria; c) guiding generation of alternatives; d) weighting the objectives and criteria; e) evaluating the performance of the alternatives; f) aggregating the scores; g) analysing the results and guiding decisions.

In BRIDGE alternative modifications of the metabolism of urban systems with the goal of sustainability are provided for the planning objectives. Criteria will be selected using a set of sustainability indicators for urban system assessment. In order to cope with the complexity of urban metabolism issues, the objectives have to 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 BRIDGE 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.

BRIDGE DSS development is based on an analytical and a design component, linking the bio-physical processes in urban environment with socio-economic parameters to estimate the environmental impacts and the socio-economic benefits of urban metabolism. The analytical component supports the assessment of the socio-economic and environmental implications of physical flows, while the design component supports the optimised land use arrangements. The DSS system offers tools to evaluate different planning alternatives. A sensitivity analysis will be used to address “what if” questions. The DSS will relate these environmental benefits to economic benefits for the community. The MCDM module will have the role of middleware between the two DSS components. GIS is used to integrate datasets, analyse the various spatial entities, store the results and then visualize them. Numerical models will simulate the results of various actions. A Graphical User Interface will integrate all components in one system and provide the user with a tool to weight the objectives and criteria of the planning alternatives under evaluation.

4. Conclusions

A central objective of sustainability is to decouple conventional resource use from economic development through technological innovation, improved efficiency and changes in individual practices. One of the biggest challenges to sustainable development is a more responsible management of natural resources. 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 a bottom-up approach to urban metabolism is needed and ICT has the potential to support this approach by providing tools and techniques (environmental modelling and simulation, software tools and databases, environmental monitoring systems and GIS, industrial ecology, decision support systems, etc.) for understanding the environmental impacts of a community's industry, commerce, infrastructure, and household behaviour as a whole system.

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 out in the framework of the project BRIDGE aims at contributing to this by devising innovative planning strategies. Several studies have addressed urban metabolism issues, but few have 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. The innovation of BRIDGE lies in the development of a DSS integrating the bio-physical observations with socio-economic data and models. It will allow 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.

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