Towards an evolutionary model of city sustainability

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Abstract

In part stimulated by the computer game industry, reasonable progress has been made in the dynamic modelling of urban growth and land use change. However, sustainability considerations in this work remain to be addressed. Yet the environmental impact of cities, already accommodating around half the global population, is both profound and increasing. It is thus important that our cities evolve in the most sustainable way possible. To guide this process it is useful to pose and test alternative urban planning scenarios. To this end, we propose the development of a new advanced computer modelling paradigm and discuss progress that is under way to realise it. In this we discuss developments in modelling the urban microclimate, the operation of buildings and services and the behaviour of humans. We also discuss ways of evaluating energy and matter flows and the potential to handle transportation and social and economic preferences in decision making. Finally, we consider this capability within a framework that will support self-organising city evolution to evaluate the future fitness of alternative planning strategies.

1 A brief history of urban energy simulation

It was only during the late 1990s that research in simulating the environmental performance of the built environment started to shift from individual buildings to the urban scale. Initial work had the rather modest objective of aiding city planners to target investments and subsidy programmes to improve energy conservation and the uptake of solar thermal and photovoltaic panels in existing residential buildings, by linking simplified energy modelling tools to Geographical Information System (GIS) software (Jones, 1999; Gadsden et al, 2000, 2002). Irradiation modelling methods were also developed to refine these analyses (Compagnon 2000, 2004; Mardaljevic, 2000; Montavon et al, 2004, 2006), but these were independent of building energy demands. An attempt was also made to use a simplified energy model to investigate relationships between urban form and non-domestic energy use (Ratti et al, 2000, 2005). However, these models were crude in their calculation of solar radiation transmission and heat flows in buildings, no attempt was made to account for the effects of stochastic human behaviour or the thermal microclimate, modelling of renewable energy technologies was either incomplete or inexistent and no means was provided for the centralised management of resources (such as district co-generation). This was the objective of Project SUNtool (Robinson, 2005; Robinson et al, 2003, 2006).

With an easy to use graphical user interface the user is able to quickly sketch an existing or proposed urban neighbourhood. An intelligent defaults mechanism supports the rapid attribution of these buildings (construction, occupation and plant characteristics) – though these characteristics may be easily refined. Embedded or centralised energy conversion technologies may also be easily defined. When ready the description is parsed to the SUNtool solver (Figure 1), which has a reduced dynamic thermal model at its core (Déqué et al, 2000). This takes inputs from a detailed shortwave and longwave radiation model which considers obstructions to both sun and sky as well as reflections from adjacent obstructions (Robinson and Stone, 2004). Predictions of internal illumination from the same model (Robinson and Stone, 2005, 2006) and indoor temperature are input to a family of stochastic models (Page et al, 2005) which simulate occupants' presence (Page et al, 2006) and their interactions with lights and shading devices; windows; water and electrical appliances as well as refuse production. The thermal and electrical demands are linked with an energy centre model, which may be building-embedded, centralised or both. Annual hourly resource flows of 100 buildings are solved for in under 15mins on a standard PC, but this increases linearly with the number of permutations defined using a simple parametric engine (a range of pre-defined parameterised variables may be adjusted between lower and upper bounds according to some user defined increment).

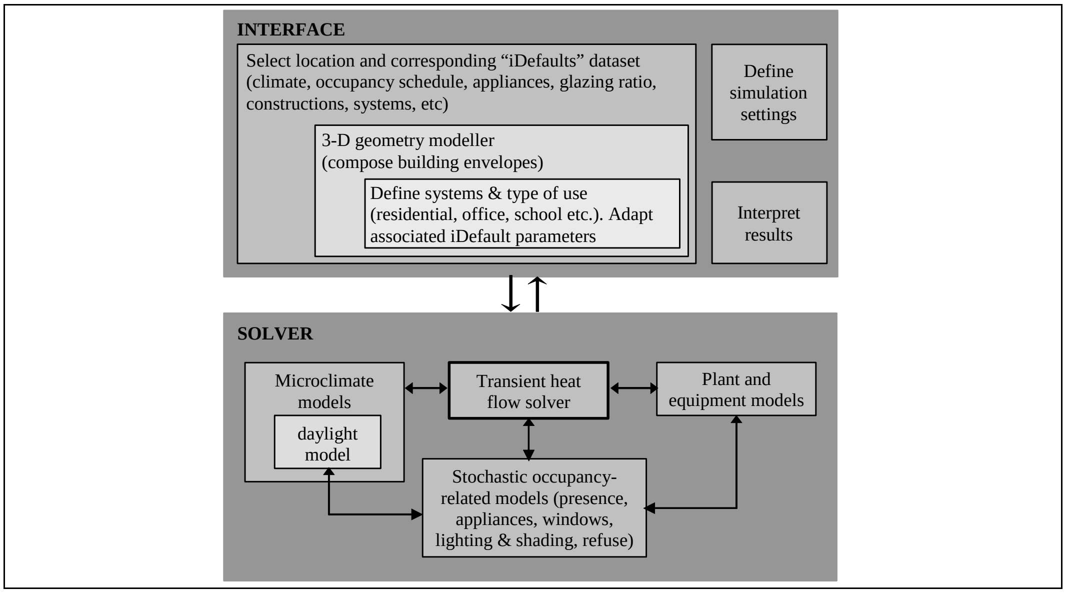

Figure 1: Structure of SUNtool

2 A more holistic model of urban sustainability

Due to the non-trivial nature of the problem (see Robinson, 2006) SUNtool does not simulate the urban thermal microclimate. Furthermore only a limited parameter space can be explored by the parametric engine in the search for an optimal solution. Finally, the interpretation of flows of energy and matter (restricted to water and refuse) is somewhat trivial: no attempt is made to properly evaluate the sustainability of alternative urban design scenarios[29]. Some such integrated evaluation would assist in the search of an optimal solution, so that the two are interlinked. These are some of the issues currently being explored at the LESO-PB/EPFL as part of the Swiss National Science Foundation's National Research Programme 54.

In this research we increase the scale of our problem somewhat, from that of the neighbourhood (of say two hundred buildings) to the district (of several thousand).

2.1 Urban thermal microclimate

Due to a complex set of thermal interactions, cities are on average warmer than their rural counterparts (the so-called heat island effect), but not always so. The magnitude of the urban-rural temperature difference varies both spatially and with time. To model the dynamic hydrothermal characteristics of a city we require a mesoscale atmospheric model, in which the thermal and mechanical interactions with the built surfaces are parameterised (explicit modelling is currently a computationally intractable problem and accurate resolution of turbulence is almost impossible because of the lack of governing

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[29] This is in part due to limitations in scope. For example the scale of SUNtool is incompatible with the modelling of private and public transport, the consumption of materials is not considered (whether over short [food, clothing], medium [furniture, automobiles] or long [constructional] timescales) and the water model is only partially complete.

equations for the unknowns involved (Stull, 1988))[30]. Starting from Martilli's (2001) urban parameterisation scheme within the LPAS/EPFL mesoscale atmospheric model, progress is underway to realise this objective. In this we aim to develop geometry-specific parameterisation schemes (in place of a repeated generic geometry) and improve the computational efficiency of the calculations.

As well as facilitating more accurate predictions of urban energy consumption[31], this will enable us to explore ways in which urban form and surface characteristics (optical and radiometric properties, extent of vegetation etc) can modify the urban heat island.

2.2 Optimisation

For a new urban development, even with a relatively limited number of variables (geometry, type of use, occupancy and constructional characteristics, plant and energy supply technologies), the number of permutations is overwhelmingly large and the probability of identifying an optimal configuration of these variables by manual trial and error is correspondingly small[32]. It is thus appropriate to use computational methods to efficiently explore this parameter space in the search for promising optimal solutions.

Candidate methods include direct, indirect and heuristic search. Direct methods search for the optimal configuration in a random way (e.g. Monte Carlo Simulation). Although faster than manual trial and error, this remains inefficient. Indirect methods use mathematical tricks to identify an optimum in the parameter space. For example, by moving in a direction of steep gradient (hill-climbing) where the solution should lie, but this optimum may be a local and not a global one. Improved efficiency is thus contrasted by uncertainty. Heuristic methods adapt according to what they have learnt about a given system. One such example is Genetic Algorithms, which use principles of natural selection to evolve to a 'fit' solution using phases of selection, cross-over and mutation. Such methods are both robust and efficient and can be applied to a wide variety of problems. They are thus our most promising candidate. Irrespective of the method chosen, some form of goal function, in our case a sustainability indicator, is required.

2.3 Evaluation of sustainability

For the present, we restrict ourselves to an environmental definition of sustainability. Whether thermodynamic[33] (energy, exergy or entropy: thermodynamic or statistical) or non-thermodynamic (e.g. ecological footprint, sustainability indicator or multi-criteria analysis) or both, our application of these methods of evaluating urban sustainability is likely to be rooted in an ecosystem approach to cities. In this way we will be able to address strategies such as reducing waste and pollution production by increasing internal systems' efficiency and closing open loops in existing metabolic flows (e.g. deriving energy from waste).

3 Towards integrated evolutionary modelling

The work described in §2, will provide us with a more complete view of urban sustainability and help us to identify how to optimise it – for a particular snapshot in time. However, cities are not static entities. They evolve in time, in response to a complex blend of social, financial and legislative stimuli, whether internally or externally generated.

Furthermore, city metabolism leads to the processing of energy and matter to support a richer set of activities than dealt with above. These include industrial processes and services (including schools, hospitals and leisure activities)[34] in addition to the residential and commercial activities currently supported by the urban models (SUNtool and the extensions discussed in §2). Furthermore, energy and

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[30] However, it is in principal computationally tractable to couple a local microclimate model with a mesoscale model. In this way we can account for background warming en-route to a particular urban locale, as well as the local processes influencing air temperature and pressure (and thus velocity) – so that we have a reasonably realistic prediction of the local microclimate.

[31] Building thermal energy consumption is influenced by 5-10% per Kelvin temperature difference.

[32] Although the parameter space is smaller for a refurbishment exercise, this space is still very, very large.

[33] The E**m**ergy method of Odum and Brown may arguably be included in this category.

[34] These unusual uses may be accounted for using empirical data or empirically derived models.

matter, as well as resources such as human labour (commuters), are exchanged across the city boundaries as well as within it, and this entails transportation.

In summary we have a set of residential, industrial, commerce, transport and service processes that lead to exchanges of energy, matter and information within and beyond the city. These exchanges influence drivers of change, such as internally or externally generated investments, planning / regulatory decisions. Social responses to these internal dynamics and to external influences may also lead to migration within or beyond the city limits. Even without this migration, the city population is in a constant state of flux (birth and death). This complex set of interactions is represented in Figure 2.

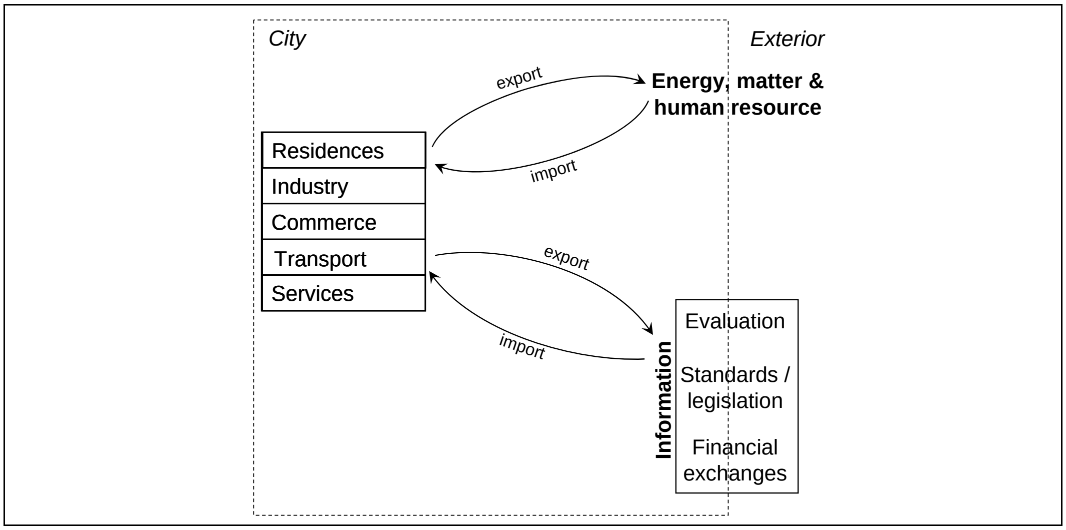

Figure 2: Conceptual Structure of a Possible Evolutionary Model of City Sustainability

We see two alternative approaches to modelling this dynamical system: a macroscopic system dynamics approach and a microscopic multi-agent approach.

The system dynamics (SD) approach would study a city as a system of characteristic stocks, such as population, built and natural environment, urban infrastructure, resources, products and waste, transport, funds etc. The state variables associated with the stocks, which evolve dynamically due to various exchanges between them, can be reduced to fluxes of energy and matter. Furthermore, causal links and feedbacks, not directly associated with energy-mass transfer but which influence the variables' dynamics, may be represented. One attraction of this macroscopic system dynamics approach is that it enables us to represent real city dynamics and complexity within a readily understandable and testable theoretical structure, allowing us to isolate and gauge the importance of causal influences for change.

Another promising vision of a city can be developed by employing a multi-agent modelling (MAM) approach. This method attempts to model decision processes of interacting groups of urban agents (e.g. residence, industry, commerce, transport, service, see Fig.2) considering their individual interests and values. The evolution of an urban system would then be an autonomous process, determined at each time step by interaction mechanisms among different agents. Sustainability (one element of the category 'evaluation' shown in Figure 2) may be regarded as an (implicit) objective of a dynamic multi-agent system where each agent tries to achieve its own goals (Nijkamp, 1994). This agent-based approach is particularly advocated for its ability to model emergent properties of complex adaptive systems, cities being one such example, as well as the self-organising character of urban evolution (Batty, 2005). This more explicit representation of the dynamics of growth and change could thus enable us to track the self-organised evolution of a city, given a set of planned influences, such as spatiotemporally explicit planning strategies or economic investments.

4 Practical Implications

Recently completed, SUNtool (§1) (www.suntool.net) is uniquely capable of simulating the range of building-related urban resource flows. In this, the purpose of SUNtool is to support urban planners and designers to optimise the environmental sustainability of their urban projects. This may involve minimising nett CO_2 emissions as a function of the placement and geometry of buildings, the design of their facades, the mix of uses accommodated by buildings (e.g. to stabilise the aggregate energy demand profile) or indeed the mix of sustainability technologies used to satisfy their resource demands. This is achieved using an easy to use graphical user interface, associated productivity aids and a fast yet accurate simulation program. In the near future the user may benefit from further computational support. For example by choosing a list of design/operation parameters which the computer may vary, the range of permutations and combinations could be exhaustively (yet efficiently) searched (§2.2, 2.3) to identify the most promising solutions. This may provide a rich source of stimulation to the designer – identifying promising previously unconsidered options.

With an accurate urban microclimate simulation program (§2.1) we will be able to identify the urban design variables which exert the greatest influence over the urban heat island effect. This in turn will help us to understand how best to manipulate this effect. For example, we may wish to accentuate this in cold climates or to diminish it in warm climates. This work is currently in progress, but we plan to investigate existing as well as hypothetical cities with a view to generating urban design guidance for microclimate control.

Our most ambitious yet exciting challenge relates to the prospect of developing new models to study the evolutionary dynamics of urban metabolism (§3). This will enable us to initially describe the existing state of a city in a way in which all key resource flows (energy, matter, money, information…etc) due to each process (residential, industrial, transport…etc) are represented and appropriate calibrated. Likewise the feedbacks between these processes. A macroscopic (SD) model would enable us to readily identify key processes in the city that should be targeted to improve its sustainability, as well as those to which the evolution of a city is highly sensitive. For example, in the absence of further outside investment a city may decay leading to unemployment, depopulation and rising crime. On the other hand, with increased internal investment this trend may be reversed. Due to a combination of legislation and increased resident sensitivity to the environment (with a consequent feedback to corporate sensitivity), quality of city life may be improved and the environmental impacts of this reduced. Once again computational optimisation methods could be used to identify promising strategies which lead a city to evolve along a sustainable pathway. Unlike SD models, the microscopic (MAM) approach simulates the exchanges between urban agents in a spatially explicit way. This would thus enable us to explore local competition between different agents (e.g. commerce, industry, residence) for urban space as well as explicit simulation of the resource demands of these agents. In addition to high-level strategies discussed above, low level strategies could be investigated – for example creating hot-spots of agent diversity to reduce transport demands (e.g. from home, to work, to leisure etc), improving the quality of the urban fabric to reduce building resource needs or optimising synergetic exchanges between buildings (e.g. waste heat from one as a resource from another) or between resources (e.g. the derivation of energy from waste). The complication however, is that with a great many agents all acting autonomously it is relatively straightforward to observe how a system evolves, but somewhat complex to understand why. Both approaches nevertheless offer exciting prospects to improve our understanding of how best to ensure that our cities maximise their sustainability not only now but into the future too.

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References

Batty, M. (2005), Agents, Cells and Cities: New representational models for simulation multi-scale urban dynamics, Environment and Planning A, vol. 37, 1373 – 1394.

Compagnon, R. Raydan, D. (2000), Irradiance and illuminance distributions in urban areas, Proc. PLEA 2000, Cambridge UK, July 2000, p436-441.

Compagnon R. (2004), Solar and daylight availability in the urban fabric, Energy and Buildings, 36(4), p231-328.

Déqué, F., Ollivier, F., Poblador, A., (2000), Grey boxes used to represent buildings with a minimum number of geometric and thermal parameters, Energy and Buildings, 31(1) 2000, p29-35

Gadsden, S., Rylatt, M., Lomas, K., Robinson, D. (2002), Predicting the urban solar fraction: a methodology for energy advisers and planners based on GIS, Energy and Buildings, 1458, p1-12.

Jones, P.J. et al (1999), An energy and environmental prediction tool for planning sustainability in cities – a global model, Proc. PLEA'99, Brisbane, Australia, p789-794.

Mardaljevic, J. Rylatt, M. (2000), An image-based analysis of solar radiation for urban settings, Proc. PLEA 2000, Cambridge UK, p442-447, July 2000.

Martilli, A. (2001), Development of an urban turbulence parameterisation for mesoscale atmospheric models, Unpublished PhD Thesis, Ecole Polytechnique Fédérale de Lausanne.

Montavon, M., Compagnon, R., Scartezzini, J-L. (2004), Comparison of the solar energy utilisation potential of different urban environments, Proc. PLEA 2004, Eindhoven, Vol. 2 p501 -506, 20th - 22nd Sept. 2004.

Montavon, M., Robinson, D., Scartezzini, J-L., Compagnon, R. (2006), Urban daylight and solar radiation potential: analysis of three Swiss districts, Energy and Buildings (in press).

Nijkamp, P. (1994), Sustainable cities in Europe. Earthscan Publications, London.

Page, J., Morel, N., Robinson, D., Scartezzini, J-L (2005), Simulating stochastic demand of resources within an urban neighbourhood, Proc. CISBAT 2005, Lausanne.

Page, J., Robinson, D., Morel, N., Scartezzini, J.-L. (2007), A generalised stochastic model for the prediction of occupant presence, Energy and Buildings (submitted).

Ratti, C., Robinson, D., Baker, N., Steemers, K. (2000), LT Urban – the energy modelling of urban form, Proc. PLEA 2000, Cambridge, July 2000.

Ratti, C., Baker, N., Steemers, K. (2004), Energy consumption and urban texture, Energy and Buildings, 37(7) 2005, p762-776.

Robinson, D. (2006), Trends and research needs in energy and comfort prediction, Proc. Comfort and energy use in buildings, Windsor UK, April 2006.

Robinson, D., Campbell, N., Gaiser, W., Kabel, K., Le-Mouele, A., Morel, N., Page, J., Stankovic, S., Stone, A. (2007), SUNtool: A new modelling paradigm to optimise urban sustainability, Solar Energy (submitted).

Robinson, D., Stone, A. (2006), Internal illumination prediction based on a simplified radiosity algorithm, Solar Energy, 80(3) 2006, p260-267.

Robinson, D. (2005), Decision support for environmental master planning by integrated flux modelling, Proc. CISBAT 2005, Lausanne, 2005.

Robinson, D., Stone, A. (2005), A simplified radiosity algorithm for general urban radiation exchange, Building Services Engineering Research and Technology, 26(4) 2005, p271-284.

Robinson, D., Stone, A. (2004), Solar radiation modelling in the urban context, Solar Energy, (77)3 2004, p295-309.

Robinson, D., Stankovic, S., Morel, N., Deque, F., Rylatt, M., Kabele, K., Manolakaki, E., Nieminen, J. (2003), Integrated resource flow modelling of urban neighbourhoods: Project SUNtool, Proc. Building Simulation 2003, Eindhoven 2003.

Stull, R.B., (1988), An introduction to Boundary Layer Meteorology, Kulwer, Atmospheric Science Library Academic Publisher.