520: Towards comprehensive simulation and optimisation for more sustainable urban design

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Abstract
In this paper we discuss progress that has been made in modelling of urban resource flows to support urban designers to optimise the sustainability of their design and planning proposals. In particular we consider models of (i) resource availability, (ii) energy demand and (iii) more general resource flows. We also critique this and from this discuss work that is underway to improve the scope of more complete resource flow models as well as probability with which users will be able to identify optimal configurations of available parameters describing their urban models. Finally we conclude by discussing ways in which building models could be coupled with models of land use and transport interaction for more complete prediction of urban sustainability and how this might evolve with time.

Keywords: Urban resource flows, simulation, optimisation

1. Introduction
It is estimated that over half of the global population is now living in urban settlements (UN, 2004), in which three quarters of global resources are consumed (Girardet, 1999). Energy derived from fossil fuels is key amongst these resources, so that urban settlements are responsible for the majority of greenhouse gas emissions and associated climatic disorders. These settlements are also estimated to cover just 2% of the earth's surface (Girardet, 1999), so that urban inhabitants are potentially highly vulnerable to the adverse consequences of climate change. There is thus a global imperative to better understand how to improve the sustainability and reduce the vulnerability of new and existing urban settlements.
Although we can learn a great deal from retrospective analysis of what has made previous urban settlements rather successful, we also need some basis for predicting the performance of future urban design proposals. We need a more rational basis for decision making in urban design, based on an improved quantitative understanding of urban sustainability. As recently concluded at the Global Humanitarian Forum:

> "ecologically sound principles [should be used to] guide urban development… new cities [have to] become more human and urban design should be based on better modelling and knowledge gathering" (GHF, 2008).

In this article we will review progress that has been made during the last decade to simulate the environmental performance of urban settlements. In this we will initially address models of resource availability before focussing on energy and more general resource flow models. We will also identify gaps in current modelling capabilities, strategies by which these gaps may be filled and work that is underway to do so. In this the aim is to model both building and transport related resource flows, their temporal evolution and how this may be optimised.

2. Urban Resource Availability
Modelling the availability of solar radiation in urban settings has a reasonably long history, dating back to simple computer models to assist with site layout planning (e.g. Everett, 1980; Knowles, 1981). More recent work has focussed on modelling the availability of solar radiation for solar energy conversion (using solar thermal collectors or photovoltaic cells) or to offset demands for applied energy for heating or lighting buildings (passive design).
In particular, this has involved the development of techniques for simulating annual solar irradiation ($Wh.m^{-2}$) incident on urban surfaces using the ray tracing program RADIANCE. Mardaljevic and Rylatt (2000, 2003) developed a method of post-processing renderings of urban scenes simulated for a statistical subset of sky-types and sun positions to create renderings of annual solar irradiation as well as hourly solar irradiance ($W.m^{-2}$). Compagnon (2000, 2004) developed an analogous method, but this time based on *pre*-processing the sky radiance distribution – creating a cumulative sky radiance distribution ($Wh.m^{-2}.Sr^{-1}$) – rather than *post*-processing results for individual skies / suns. Moreover, Compagnon produced irradiation results for individual (r-trace) points within the urban scene which could later be analysed to determine to the proportion of urban surfaces which exceed specific thresholds relating to the viability of passive and active solar energy technologies.

Robinson and Stone (2004) developed a slightly more computationally accurate way of simulating irradiation using a cumulative sky (by discretising the sky rather than using individual light sources). By way of example, in Figure 1 we present a rendering of urban irradiation for the district of Matthaüs in Basel, Switzerland. In Figure 2 we present cumulative irradiation distributions for the three Swiss urban districts of Matthaüs (Basel), Bellevaux (Lausanne) and Meyrin (Geneva).
The first image is visually interesting, but the second, derived from Compagnon's work, enables us to understand in quantitative terms the potential to utilise solar radiation, at a glance.
But this work represents just one angle of attack – conversion of solar energy into thermal or electrical energy to meet buildings' energy demands. It is also important to understand the potential for minimising these demands.

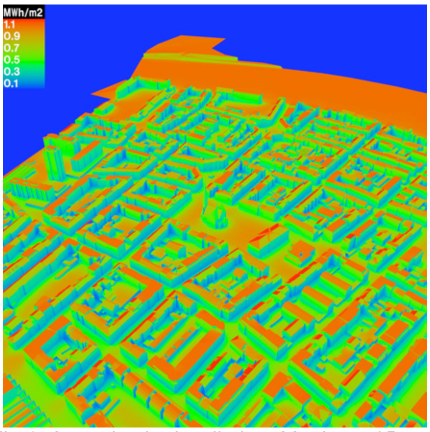

Fig 1. Annual solar irradiation: Matthaüs / Basel, Switzerland.

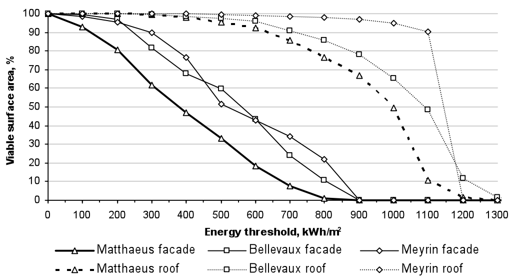

Fig 2. Annual solar irradiation distributions for three Swiss districts.

3. Urban Energy Modelling

Advances to date have been based on predicting the energy demands of groups of residential or of commercial buildings as distinct categories.
In the UK Jones et al's (1998, 1999, 2007) model EEP estimates the energy demands and associated emissions for a municipality's stock of buildings based on extrapolation of results from representative building typologies (100 for the case study site of Neath and Port Talbot) – descriptions of these being informed by field survey data. A similar approach has been developed to model the domestic building stock of Osaka in Japan (Shimoda et al, 2003), based on extrapolation of results from 460 combinations of building type and size and household composition. A key difference in emphasis however, is in the representation of occupants' behaviour using detailed survey statistics which relate activities (particularly occupants' presence and use of appliances) to household composition. Gadsden et al (2003) on the other hand, explicitly model individual buildings to determine the potential for reducing energy demands through better utilisation of solar energy as well as for installing solar energy conversion systems to meet this demand.
Yamaguchi et al (2003, 2007) predict the energy performance of individual commercial buildings, based on building-specific descriptions of their constructional and occupancy characteristics. In the absence of time-use survey data, a basic stochastic model simulates occupants' weekday presence (arrival, lunch and then departure) and, whilst present, whether they are using one or two PCs or none at all; this depending upon their type of job. Other electrical loads (incl. lighting) are deterministically predicted on the basis of installed capacity and schedule of use. Heat gains from these electrical loads are then input to a space conditioning demand model. Given a system coefficient of performance, this load is translated into an energy demand. Results from all buildings within a given case study zone are then aggregated and input to a district energy supply model, which simulates district heating, cooling and co/tri-generation systems as well as thermal distribution losses.
More recently, Yamaguchi et al (2007) have increased their scale of analysis to that of the city, based on extrapolation from a sample of building types. This model has also been run in tandem with Shimoda et al's (2003) model to predict the performance of the entire residential and commercial building stock of Osaka (Shimoda et al, 2007), to study the implications of telecommuting on building energy demand.
The above models have been developed with the aim of supporting municipalities to improve the energy performance of their stock of buildings. They have not been developed as design tools for use by architects and planners to test alternative scenarios for a particular new or existing development. They also tend to lack some basic modelling functionality:

- Modelling the effects of adjacent buildings on reducing diffuse sky and direct solar radiation as well as their contributions to reflected radiation is either absent or partial.
- Modelling of the effects of the urban meso / micro-climate on buildings' energy balance is ignored.
- Human behaviour within buildings is either represented by deterministic profiles, survey data or based on rather simplified stochastic models of a sub-set of the key processes influencing buildings' energy demands.
- Modelling of supply from and control of energy conversion systems, whether embedded or locally centralised, is limited.

4. Urban Resource Flow (URF) Modelling

Partially in response to the above limitations, the software SUNtool (Sustainable Urban

Neighbourhood modelling tool) was conceived as a decision support system for designers to optimise the environmental sustainability of masterplanning proposals (Robinson et al, 2003, 2007), based on integrated resource (energy, water and waste) flow modelling of buildings of disparate uses. A further guiding principle of SUNtool was that the predicted resource flows should respect their sensitivity to the urban climate, to human behaviour and to possible couplings between buildings and between buildings and systems, which may be embedded or centralised (Robinson, 2005).

On starting a masterplan modelling project (see Figure 3), the user first chooses / enters the geographical location, to set the site coordinates and associate the site with climate data. The user is then invited to select a relevant 'iDefault' dataset; that is, a database of default attributes (occupancy, constructional, plant systems etc) for the range of building types. The software's sketching tool may then be used to develop a three-dimensional description of the site. Building objects are assigned a default use (residential), but this may be overridden, so that the appropriate characteristics are assigned to the building. Likewise any building or façade-specific characteristics may be easily overridden, by clicking on the corresponding object. Solar (thermal or electric) collectors may be associated with building surfaces in a similar fashion. Specific buildings may also be selected for association with a district energy centre, for locally centralised resource management.

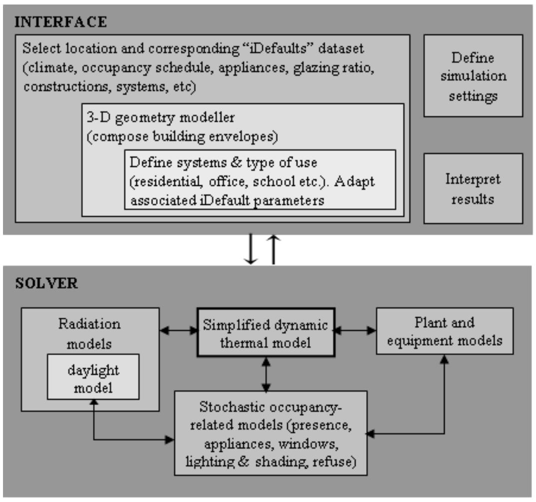

Fig 3. Conceptual structure of SUNtool

When a site description is complete this is parsed to the SUNtool solver, in which there are four principle families of model: radiation, thermal, stochastic and plant.

Note that there is potential feedback between these families of model. The radiation model influences the internal space conditions predicted by the thermal model and this in turn influences the calculation of external longwave radiation exchange. The magnitude of transmitted daylight (as well as the position and radiance of the sun) influences users' behaviour of lights and blinds, which in turn influences the prediction of interior daylight levels. The thermal inputs arising from occupants' behaviour influence the internal space conditions predicted by the thermal model and this in turn may influence their behaviour (e.g. in respect of window openings). The thermal energy demands for space conditioning may be adjusted by psychrometric processes within air handling plant. Furthermore, plant systems (whether air handling or otherwise) may not have the necessary capacity to meet the buildings' demands, with implications for the indoor thermal environment. Furthermore, the delivery of thermal energy by fluid networks (pipes and ducts) may incur electrical energy demands. These demands, coupled with those predicted by the stochastic models may or may not be satisfied by the available electrical energy production plant, whether embedded or centralised. The basis of these models is described in Robinson et al (2007).

Batches of simulations may be prepared, relating to a selected group of buildings and for a chosen period of time. Alternatively, parametric studies may be performed. For this latter certain parameters may be varied between user-defined lower and upper limits according to some chosen increment. The associated results are streamed back to the interface from the solver via XML files. When complete line graphs and summaries of results may be interrogated and buildings may be false-coloured according to the magnitude of certain variables. Animations of the evolution of these falsecoloured plots may also be displayed.

4.1 Limitations in SUNtool

On the whole SUNtool responds well to the basic modelling weaknesses identified above in relation to urban energy models. It accounts for the radiant environment, human presence and behaviour and a range of embedded and locally centralised energy conversion systems. It also explicitly models the energy needs of heating, ventilating and air conditioning plant. Crucially, it is has been conceived as a design tool for use by architects, planners and engineers and repeated applications of the software at the Ecole Polytechnique Fédérale de Lausanne (EPFL) suggest that the software performs well in this respect (albeit in prototype form).

But SUNtool has some limitations of its own relating to its current modelling capability. The thermal model lacks generality, the stochastic modelling of human presence and behaviour is incomplete (the appliance model is not enabled and only limited prototypes of the other models are integrated), not all key energy conversion systems are modelled, there is no model of energy storage associated with building or district energy centres and modelling of water and waste flows is somewhat limited. Furthermore, it is unlikely that the user will be guided towards an optimal configuration for a particular project simply by automating parametric simulations for a limited range of variables.

Despite these limitations, SUNtool does currently represent the state of the art in modelling software to support sustainable masterplanning.

5. Towards Comprehensive Simulation & Optimisation of Urban Resource Flows

Work at the Solar Energy and Building Physics Laboratory at EPFL has concentrated in recent years in consolidating the core capability of SUNtool discussed above and in increasing its scope to that of the urban district (of several hundreds of buildings) with the eventual aim of simulating and optimising entire urban settlements (towns or cities). For the moment we call this successor LESO-SUNtool.

5.1 Basic model consolidation

The model consolidation effort has involved numerous developments. For example, the thermal model has been replaced with a more general model based on an electrical network analogy (Kämpf and Robinson, 2007). Models of latent and sensible heat storage have also been added to a more complete family of HVAC and energy conversion system models. A completed version of a model of occupant presence (Page et al, 2007) has been integrated alongside more recent developments related to the stochastic modelling of interactions with appliances (Page et al, 2008) and with windows (Haldi et al, 2008). Furthermore, a more efficient algorithm for calculating the view parameters needed by Robinson and Stone's (2005) Simplified Radiosity Algorithm (SRA) has been developed. In short the core modelling of building-related energy flows is now rather complete.

5.2 Additional core features

The energy flows during the operation of an urban development are just part of the story. It is also of interest to also consider the embodied energy content of materials, to facilitate life cycle energy analysis. Related to this is an issue of primordial importance to the urban designer and developer – that of costs (both capital and running). Realistically speaking, this typically outranks environmental performance as a fitness function to optimise. Work is thus underway to add these additional attributes (cost and embodied energy) to the properties of the constructional objects which comprise an urban scene being modelled with LESO-SUNtool.

We have thus far focussed our discussion on energy modelling, but SUNtool was also conceived to support the modelling of key matter flows within an urban development. In this we restricted ourselves to (i) the consumption of water, the collection and storage of rainwater and the collection, treatment and re-use of greywater, and (ii) the separation of waste to estimate the potential for recycling. These simple facilities will be retained in LESO-SUNtool but we will also, in the short term, support modelling of the derivation of energy from waste – either by biogas production or solid waste incineration.

In the longer term, as we increase our scale of analysis as well as the diversity of building types that are modelled, it will be of special interest to model possible synergetic exchanges of energy and matter between buildings. In this way it will be possible to test hypotheses inspired by industrial ecology regarding ways of minimising net urban resource use, through improved circularity in their flows. Consider the town of Kalundborg in Denmark for example. Amongst the numerous synergetic exchanges the waste heat produced by the power station meets the space heating and hot water demands of the towns' buildings and a fish-farm as well as the process heat needs of a bioplant and an oil refinery. The bioplant produces yeast for pig farmers as well as fermentation sludge for local farmers…and so on. The reduction in resource imports and exports are considerable. Since the processes involved may be represented in an aggregate way (as is typical with mass flow analysis), representing the potential exchanges need should not be difficult.

Due mainly to differences in radiant exchanges, the presence of anthropogenic sources, reduced evaporative sinks and mean wind speeds, urban settlements are warmer <u>on average</u> than adjacent rural settings. This so-called heat island effect has an impact upon buildings' energy balance and so we should consider this in urban scale energy demand predictions. To this end progress is being made at EPFL (and elsewhere) to develop a meso-scale atmospheric flow models in which thermal and mechanical interactions between air and built surfaces within the urban canopy layer are parameterised (Rasheed et al, 2007, 2008). This model will produce predictions of urban air temperature, wind speed and direction for an urban grid spacing of around 500m. These pre-processed results may then be read-in by the urban resource flow model, as for a standard climate file.

5.3 Computational 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 very large. Although the parameter space is smaller for a refurbishment exercise – in principle the geometry and some constructions will be retained – it remains large. The probability of identifying an optimal configuration of these variables by manual trial and error or simple parametric studies is thus correspondingly small. It is appropriate then 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 more reliable 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.

Following from a review of available evolutionary algorithms, we have developed a hybrid of two algorithms (Covariance Matrix Adaptation – Evolutionary Strategy [CMA-ES] and Hybrid Differential Evolution [HDE]) which offers improved robustness over its individual counterparts for a larger range of optimisation problems (Kämpf and Robinson, 2008).

As a starting point we have applied this algorithm to the relatively simple problem of optimising the layout and geometry of buildings for the utilisation of available solar radiation. First our candidate geometries are converted into RADIANCE format, a set of (*r-trace*) calculation points are then defined along with a cumulative annual sky radiance distribution for the location of interest. The simulations are the performed and individual results of solar irradiation ($Wh.m^{-2}$), associated with a given area of surface (m^2), are cumulated to determine total solar irradiation (MWh) – this being out fitness function to optimise (Kämpf and Robinson, 2008a).

We have applied this modelling utility to several interesting problems. One example is the problem of optimising tower height for a regular grid of buildings (Figure 4). Chen et al (2006) investigated a similar problem, but based on manual trial and error of a relatively small sample. Their conclusion that rather randomly dispersed tall buildings tends to optimise solar utilisation is contrasted by our result that a well organised layout, consisting of a high perimeter with a south-facing gap and a low core (the gap providing access to the southern facades of rear buildings), is optimal.

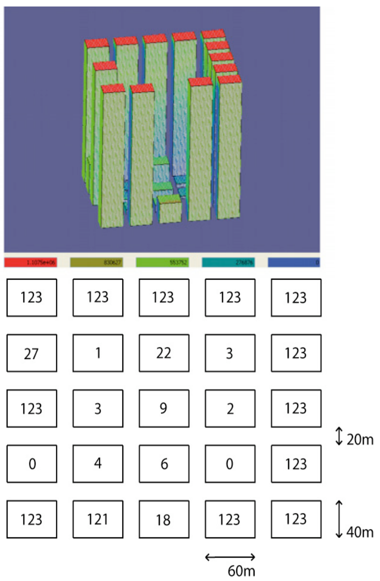

Figure 4 Optimisation of tower height within a regular grid for solar irradiation utilisation

We have also experimented with manipulating building form for solar energy utilisation. One example is shown in Figure 5 in which we have used a Fourier series to model roof geometry. It is hoped that such experiments might provide a helpful source of inspiration to architects when formulating concept design solutions for specific problems. The next step in this work is to couple our evolutionary algorithm with our urban resource flow modeller LESO-SUNtool and apply this to optimise the energy performance of the district of Matthäus, Basel.

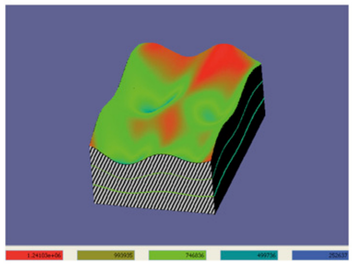

Figure 5 Optimisation of Fourier-series representation of roof geometry for solar irradiation utilisation

5.4 Coupled building · transport · land-use modelling

Good progress has been made in recent decades in the modelling of urban spatial dynamics and of transport. Indeed several computer models exist which integrate the two, to varying degrees of sophistication. But no attempt has been made to couple these with resource flow models, and so provide a comprehensive basis for modelling sustainability and how this may evolve with time. Such models could provide powerful support to urban planners to guide the development of urban settlements along more sustainable trajectories.

We may consider cities as being comprised of actors [firms, individuals] which react to economic, governance, technological and educational stimuli and to the actions of their peers. Indeed cites exhibit complex emergent behaviour resulting from these individual reactions. In principal we can model the key behavioural mechanisms of these actors. In particular we can model the:

- creation, growth and relocation of firms,
- birth, relocation and death of individuals,
- the development of buildings and infrastructure to accommodate them.

A coherent basis for achieving this is in the form of a multi agent simulation paradigm.

The next challenge is to couple transport models with building-related resource flow models. For this, multi agent simulation once again provides the answer. LESO-SUNtool includes stochastic models for predicting the presence and behaviour of occupants. A natural progression would be to model occupants as agents that perform their daily tasks, react to local environmental stimuli and move within and between buildings. For this latter, these occupants may be exchanged from buildings to relevant modes of transport and vice versa. Indeed detailed agent based transport models already exist (e.g. MATSIM). The great challenge is to achieve this objective in a computationally tractable way.

6. Conclusions

In this paper we have non-exhaustively reviewed previous research related to the modelling of urban environmental performance and given a flavour of the current state of the art in this topic. We have also attempted to define some of the directions in which current research is headed with the more ambitious aim of facilitating urban designers to simulate and optimise the sustainability of their urban design and planning proposals in a comprehensive way.

From the authors' perspectives, particularly interesting areas of current research include:

- Synergetic energy and matter exchanges
- Life-cycle (energy) cost analysis
- Meso-climate modelling as a pre-process
- Integrated computational optimisation
- Coupled building · transport · land-use modelling

Indeed, further research from other teams would usefully complement this effort.

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