OPTIMISATION OF URBAN ENERGY DEMAND USING AN EVOLUTIONARY ALGORITHM

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ABSTRACT

Computer modelling at the urban scale is an increasingly vibrant area of research activity which aims to support designers to optimise the performance of new and existing urban developments. But the parameter space of an urban development is infinitely large, so that the probability of identifying an optimal configuration of urban design variables with say energy minimisation as a goal function is correspondingly small. To resolve this we have coupled a micro-simulation model of urban energy flows CitySim with a new evolutionary algorithm (EA): a hybrid of the CMA-ES and HDE algorithms.

In this paper we present the means of coupling the EA and CitySim and identify a subset of urban design variables that have been parameterised. We then present results from application of this new methodology to minimise the energy demand of part of a case-study district in the city of Basel, Switzerland. The papers closes by discussing work that is planned to further increase the scope of this new methodology for optimising urban sustainability.

INTRODUCTION

Half of the global population now lives in urban settlements, which collectively consume three quarters of global resources. With forecasts that this urban population will increase to three quarters by 2050 it is imperative that we understand how to minimise urban resource consumption and its negative environmental consequences whilst maintaining good quality of life standards for inhabitants. For this computer modelling of resource flows can be an invaluable decision support tool for urban planners and designers.

Project SUNtool (Robinson et al, 2003; Robinson, 2005) started in 2001, with just that objective in mind. Conceived to support the environmental design of urban masterplans accommodating both domestic and non-domestic buildings, the SUNtool solver has a reduced dynamic thermal model at its core. 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 prototype family of stochastic models which simulate occupants' presence (Page et al, 2007a) and their interactions with lights and shading devices; windows; water and electrical appliances; refuse production (Page, 2007; Page et al, 2007b). The thermal and electrical demands are linked with an energy centre model, which may be building-embedded, centralised or both (Robinson et al, 2007). Based on a predictor-corrector approach, if energy supply is insufficient to meet the demand, new internal conditions are calculated in the thermal case or uses are prioritised in the electrical case.

In 2006, work started on the development of a successor to SUNtool. Called CitySim this was conceived to provide for more comprehensive simulation of resource flows at the neighbourhood scale whilst also facilitating the simulation and optimisation of these flows at larger urban scales; from the urban district to an entire city (Robinson et al, 2009).

But at the urban scale, the probability of identifying an optimal configuration of urban design variables with resource minimisation (and perhaps some indicator of inhabitant satisfaction) as a goal function is highly unlikely as the parameters space is infinitely large. Therefore, a new evolutionary algorithm (a hybrid of the CMA-ES and HDE algorithms) was developed (Kämpf and Robinson, 2008) and successfully applied to manipulate the geometric form of groups of buildings to optimise the potential utilisation of solar energy by passive and active means (Kämpf and Robinson, 2009).

In this paper, we present the means of coupling the EA and CitySim along with the urban variables that can be parameterised. We then present results from the application of this new methodology to minimise the energy demand of part of a case-study district called Matthäus in the city of Basel, Switzerland. The papers closes by discussing work that is planned to further increase the scope of this new methodology for optimising urban sustainability.

METHODOLOGY

We begin by describing some of the key principles of CitySim's structure and continue by presenting the evolutionary algorithm and how the two are coupled.

CitySim structure

CitySim comprises three parts. A graphical user interface (GUI), a defaults database containing specifications related to constructions and other parameters, and finally a solver.

The GUI allows the user to sketch envelopes of buildings within an urban site. It includes functions to manipulate the geometry such as polygon input procedures, extrude, move, scale, mirror, clone, measure and so on to enable planners and architects to sketch and evaluate the massing and disposition of buildings and the spatial qualities between them.

In common with SUNtool default characteristics describing the constructional, occupational, appliance and system's characteristics of a range of types and age categories of buildings are held in an editable database. After associating buildings with their relevant building category these default characteristics may be further refined either at the scale of the entire building or indeed for individual surfaces of the building envelope.

By default, a building is allocated an Energy Centre, which contains HVAC systems as well as the sources of energy (grid or energy conversion system) which satisfy their needs as well as those of lights and appliances. Buildings may also be associated with a District Energy Centre to provide heating, cooling or power needs. The user also inputs location and climate information.

The principle means for data exchange between the graphical user interface (GUI) and the CitySim solver, is by means of an XML file.

The solver calculation comprises four parts in sequence. Firstly, it reads the XML file and creates the scene; defined by the C++ objects describing the buildings, zones and associated plant systems. The second stage involves a sequence of pre-processes for the radiation model. This involves for example creating a sky radiance distribution and determining the sun position for each hour and calculating the view factors for the models' matrices from every surface in the scene. Thirdly, the simulation is launched, in which each model is called in sequence from within a main loop for each hour and for each building / thermal zone. The results are finally written to an ASCII file and read by the GUI for the users' interpretation.

For further details of CitySim's structure the reader is referred to Robinson et al. (2009).

Evolutionary Algorithm (EA)

For the minimisation of the energy needs of a district simulated using CitySim we need a fit for purpose method. The vast parameter space of possible and allowed changes in the urban context suggests the need for computerised algorithms rather than manual trial and error. Moreover the response function computed by CitySim may exhibit a non-linear, multi-modal and discontinuous behaviour. Therefore heuristic methods such as Evolutionary Algorithms are needed to overcome possible local optima, keeping in mind that we can never be sure of finding the global optimum in a finite time frame.

The principle behind EAs is a process equivalent to the darwinian evolution of species. It is population based, in which its evolution goes through three operators: recombination, mutation and selection. Each member of the population is a potential solution of the maximisation or minimisation problem.

We developed our own optimiser based on a hybrid of two well-known evolutionary algorithms (CMA-ES and HDE). The new optimiser proved to be consistently more robust in finding the global optimum of two standard benchmark functions (Ackley and Rastrigin) compared to the individual methods. We stress this point because in real optimisation applications, robustness has been found to be an important issue. Our hybrid optimisation algorithm should also be robust in finding good candidate solutions to other problems for which the function response to its parameters is similar to the tested benchmark functions.

In addition to the solar optimisation problems mentioned earlier, our new optimiser was successfully linked to the EnergyPlus software using template building description files in much the same way as GenOpt (Wetter, 2004) does. It was also compared to GenOpt in terms of algorithm performance and showed equivalent results (Kämpf et al., 2009). A similar method of using template description files is used in this study.

Coupling of CitySim with EA

The hybrid CMA-ES/HDE uses CitySim as a black box (see Figure 1).

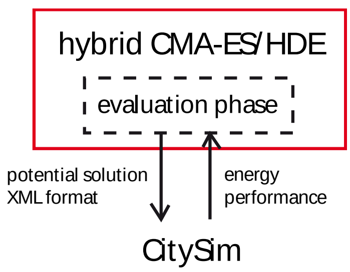

Figure 1 The black-box optimisation problem with CitySim

The first step is to create an XML template of the simulated scene, in which each parameter of the study is replaced by a special character combination. The template XML is then used by the CitySim solver in the evaluation phase to determine the potential solution's energy performance.

Urban variables that can be manipulated for an optimisation

Of the vast parameter space that can be explored at the city scale, we have defined a sub-parameter space for this preliminary study. In this the following characteristics can be changed:

- glazing ratio
- window U-Value
- position of the insulation of the walls (internal or external)
- Wall insulation thickness

Note that the glazing G-Value is held constant. For this preliminary exercise we also limit ourselves to the simulation of energy demand, so that energy conversion systems are also not considered.

APPLICATION

We have chosen to apply the methodology to the district of Matthäus in Basel (Switzerland), for which the 3D information of the whole district is available to us; likewise a subset of the national census data for the year 2000 and the results from a recent visual field survey of the district. From the CENSUS 2000, we have the construction year, last renovation date and the heating fuel used. From the district visual building survey we have the glazing ratio, the facade state and pictures. Finally, we have meteorological data measured by a weather station in Basel from the Meteonorm software.

As a first application of the methodology, we decided to use only a part of the Matthäus district.

Problem definition

For our first application of our proposed methodolody to optimising urban energy flows, we have selected a block of buildings within Matthäus located between Matthäusstrasse, Müllheimerstrasse, Klybeckstrasse and Feldbergstrasse (see Figure 2).

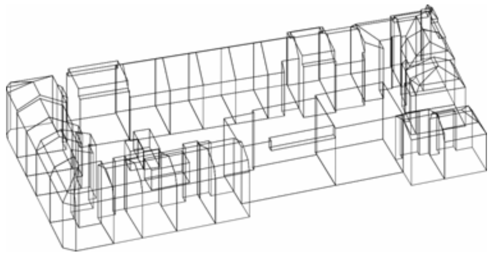

Figure 2 The part of Matthäus district in Basel, Switzerland used for the case-study

This group of buildings consists of 26 individual shelters, with construction years ranging from the beginning of the 19th century to the 1970's; with some buildings having been renovated between the 1970's and the 1990's.

With the help of renovation specialists (EPIQR Rénovation, Lausanne) we have linked the construction year / renovation date and the physical properties of the walls, roofs and windows needed by CitySim to simulate the buildings' thermal performance.

The chosen part of the district is subdivided administratively by the city authorities in three zones as shown in Figure 3.

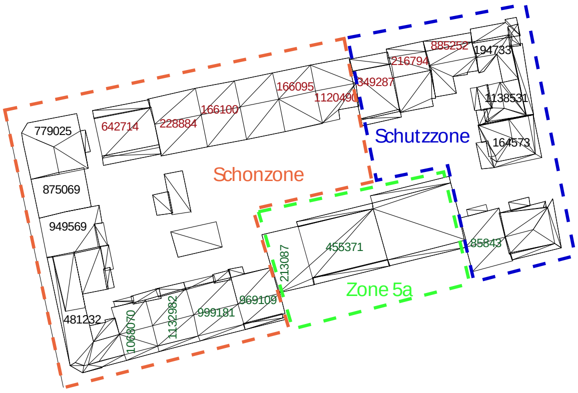

Figure 3 The three administrative zones in Matthäus district

The Schutzzone is a historical part of the city that is protected, so that we are not allowed to change the walls, the roofs and the fire walls. The Schonzone is less restrictive: only the external appearance of the building should not be modified. The remaining Zone 5a is not historical and may be modified under the approbation of the authorities.

Data extrapolation

With the geometric information available to us, we are able to load the geometry of the relevant part of Matthäus in the GUI of CitySim and complete the physical properties of each building (see Figure 4). Unfortunately, the information set was not complete for all buildings present in the sector; indeed we had nothing more than the 3D information on 4 buildings out of the 26. For this and for subsequent studies we therefore developed a procedure to infer the missing physical properties from the available data.

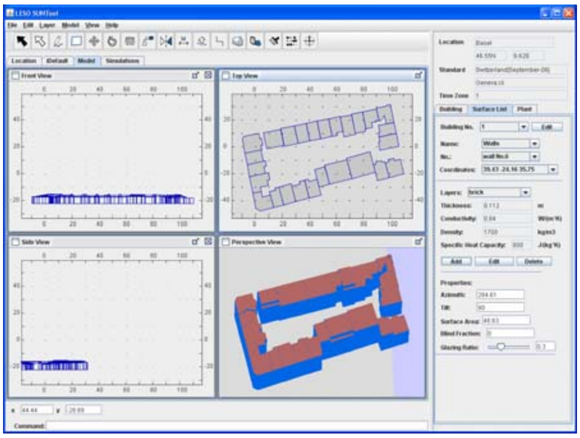

Figure 4 The part of Matthäus district imported in the GUI of CitySim

Even though neither the Census nor the visual field survey data are available for all buildings within the district of Matthäus, the data is nevertheless available for a statistically significant sample of buildings (in both cases in excess of 1000). We have therefore developed a procedure according to which we use the data available to infer appropriate attributions where this is unavailable. More specifically we derive a probability of occurrence of each value that a given variable may take (using observed data) and from this define a cumulative distribution function (CDF). We then draw a random number and, from the CDF, we determine which value of our variable this corresponds to.

Each building in the Census and visual survey have a unique identification number that allows us to make a link between the physical address on the street and the building characteristics. In Figure 3 we have superimposed the identification number on each of the buildings in our case study site.

Parameterised variables

From the sub-parameter space of urban variables that was chosen for this study we apply constraints of the allowed changes that can be made within the three administrative zones in Matthäus. In the Schutzzone we can improve the windows by adding a second frame inside the building. In the Schonzone, we can improve the windows and add internal wall insulation as these modifications are not visible from outside. Finally in the Zone 5a, we can change the windows and even add external wall insulation (which tends to perform better than internal insulation).

The XML file describing the sector is templated using the remaining variables shown in Table 1. Those variables are a subset of all variables that could be taken into account for the buildings' simulation. For this first study we have made a selection of thirteen parameters as a preliminary demonstration of our methodology.

Table 1
Variables taken into account for the optimisation with the Evolutionary Algorithm

PARAMETER	SYMBOL
Schonzone, built <1919 Walls internal insulation (cm) Windows U-Value	$x_1 \in [0,12]$ $x_2 \in [1.5,6]$
Schonzone, built '46 until '60 Walls internal insulation (cm) Windows U-Value	$x_3 \in [0,12]$ $x_4 \in [1.5,6]$
Schonzone, built '61 until '70 Walls internal insulation (cm) Windows U-Value	$x_5 \in [0,12]$ $x_6 \in [1.5,6]$
Schutzzone, built <1919 Windows U-Value	$x_7 \in [1.5,6]$
Zone 5a, built '61 until '70 Walls external insulation (cm) Windows U-value Glazing ratio	$x_8 \in [0,12]$ $x_9 \in [1.5,6]$ $x_{10} \in [0.1,1.0[$
Zone 5a, built '71 until '80 Walls external insulation (cm) Windows U-value Glazing ratio	$x_{11} \in [0,12]$ $x_{12} \in [1.5,6]$ $x_{13} \in [0.1,1[$

We have clustered the buildings by construction date, according to the physical properties of the walls, windows and roofs. The insulation can be up to 12cm thick and can be placed on the inside of the walls for the Schonzone or on the ouside of the walls for the Zone 5a. The windows' U-values may vary from the original single glazing to more recent double glazing with a low emissivity coating. Buildings' glazing ratios are considered to be the same on all facades, but between buildings this may vary from a somewhat minimal ratio to being fully glazed.

The representation of the buildings in the different age groups is as follows:

Schonzone built <1919:	14 buildings,
Schonzone built '46 until '60:	1 building,
Schonzone built '61 until '70:	1 building,
Schutzzone built < 1919:	7 buildings,
Zone 5a built '61 until 70:	2 buildings,
Zone 5a built '71 until 80:	1 building,

for a total of 26 buildings.

Objective function

The objective function used in the optimisation is the sum of the ideal heating and cooling demands (assuming that both are required, or that overheating risk – indicated by cooling energy demand – is to be minimised) for the group of simulated buildings for an average year. The heating set point is assumed to be 21°C and that for cooling to be 26°C. Each evaluation for a given combination of the available parameters takes about 5 minutes on a machine with an Opteron 2.3GHz processor and 4 GB RAM.

In total we have 13 parameters, which is convenient for a number of evaluations ranging between 3000 and 6000 and we assume that the objective function's response is similar to the Ackley or Rastrigin benchmark functions (see Kämpf and Robinson, 2009).

Note that we later plan to add to the performance evaluation procedure the capital costs, running costs and embodied energy investment for the simulated objects. These indices can then be used as constraints during the optimisation process, as a more realistic basis for solution selection.

RESULTS

After about 3000 function evaluations (or runs of CitySim), we noticed a plateau in the objective function (see Figure 5).

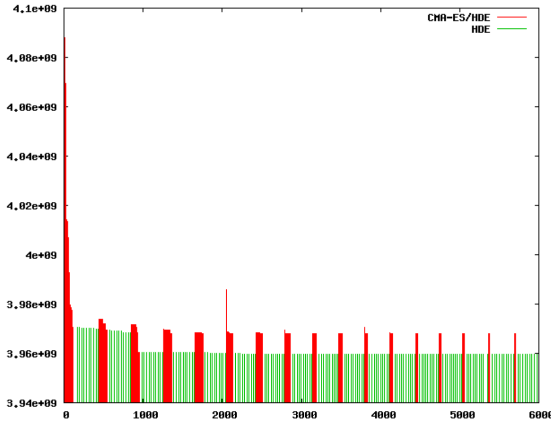

Figure 5 The evolution of the fitness (total buildings' performance) with the number of evaluations

The EA seems to have found a stable optimum in the aggregate ideal heating and cooling demands of the 26 buildings. In its current state the estimated heating and cooling energy demands for this city block is 4.95 GJ. In the optimised case this is reduced to 3.96 GJ so that even by modifying a relatively small number of constrained parameters substantial energy demand reductions (~20%) are possible.

The parameter values resulting from this optimisation process are shown in Table 2.

We notice in the results that the insulation is always increased to the maximal thickness; likewise for the windows' U-value which tends to the best available. This result is rather encouraging as it is compatible with what we would have expected. There is only one exception for the building in the Schonzone built between the 60's and the 70's, for which no insulation is proposed. In this case the wall is composed of two heavy parts (brick and concrete) separated by a layer of insulation, so that it does not require additional internal insulation, which would diminish the building's internal thermal intertia.

Table 2
Variables optimised with the Evolutionary Algorithm after 6000 evaluations

PARAMETER	SYMBOL
Schonzone, built <1919 Walls internal insulation (cm) Windows U-Value	$x_1 = 12$ $x_2 = 1.5$
Schonzone, built '46 until '60 Walls internal insulation (cm) Windows U-Value	$x_3 = 12$ $x_4 = 1.5$
Schonzone, built '61 until '70 Walls internal insulation (cm) Windows U-Value	$x_5 = 0$ $x_6 = 1.58$
Schutzzone, built <1919 Windows U-Value	$x_7 = 1.5$
Zone 5a, built '61 until '70 Walls external insulation (cm) Windows U-value Glazing ratio	$x_8 = 12$ $x_9 = 1.5$ $x_{10} = 0.21$
Zone 5a, built '71 until '80 Walls external insulation (cm) Windows U-value Glazing ratio	$x_{11} = 12$ $x_{12} = 1.5$ $x_{13} = 0.12$

For the glazing ratio in Zone 5a, a compromise had to be found to satisfy the building's needs for the whole year. As a reminder we compute the heating needs and cooling needs taking into account the irradiation on the facades that is transmitted through the glazed surface into the building. No shading control system is currently implemented. If the building is well insulated and well glazed, relatively high solar gains, necessitating cooling, can be experienced even in winter. Therefore a balance between the cooling season gains and heating season losses is needed to ensure a good performance over the whole year. For this relatively low glazing ratios (10 to 20%) are required. It is interesting to note that in contrast to the insulation position and thickness and window thermal transmittance, we would not necessarily have been able to identify these optimal glazing ratios by intuition alone.

In the next months of development of CitySim and its coupling with the EA, we plan to simulate deterministically (to reduce the complexity of the response function, in comparison with stochastic models) occupants' presence and their interactions with windows; so that for example we can simulate users' control of blinds to limit excess summertime solar gains. We also plan to model a range of energy conversion systems, such as solar thermal collectors and cogeneration systems. In this we hope to also include the costs and embodied energy implications of renovation measures to provide for a more complete basis for performance optimisation.

CONCLUSION

This paper presents a first application of Evolutionary Algorithms to optimise the performance of a group of buildings. For this we used CitySim (a holistic urban simulation tool) as a performance evaluator applied to a case study site in the city of Basel (Switzerland). For this first test we examined a selection of thirteen physical parameters associated with a block of 26 buildings grouped by construction date and protection status. In addition, we added as a constraint the protection status which is associated with some of these buildings.

The optimisation algorithm has previously been shown to perform well in comparison with other algorithms and standard benchmark functions. In this test we have also seen that the results obtained are both reasonable and physically understandable.

But this first proof of concept has been somewhat limited in scope. We will now add further complexity to our problem by account for occupants' interactions with the envelope (albeit in a deterministic way) as well as energy conversion systems. We also plan to account for renovation costs and the associated embodied energy content of installed materials / products.

For this, we will also provide for the possibility to control the optimisation algorithm from within CitySim's graphical user interface.

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NOMENCLATURE

$\vec{x} = (x_1, \ldots, x_{13})$: Optimisation variables

REFERENCES

Kämpf, J.H., Wetter, M., Robinson, D. (2009), A comparison of different optimisation algorithms in conjunction with EnergyPlus, Journal of Building Performance Simulation (to be submitted).

Kämpf, J.H., Robinson, D. (2009), Optimisation of building form for solar energy utilisation using constrained evolutionary algorithms, Energy and Buildings (submitted).

Kämpf, J.H., Robinson, D. (2009), A hybrid CMA-ES and DE optimisation algorithm with application to solar energy potential, Applied Soft Computing 9 (2009), pp. 738-745.

Page, J. (2007), Simulating occupant presence and behaviour in buildings, Unpublished PhD Thesis, EPFL, 2007.

Page, J., Robinson, D., Morel, N., Scartezzini, J.-L. (2007a), A generalised stochastic model for the prediction of occupant presence, Energy and Buildings, 40(2) p83-98, 2007.

Page, J., Robinson, D., Scartezzini, J.-L. (2007b), Stochastic simulation of occupant presence and behaviour in buildings, Proc. Tenth Int. IBPSA Conf: Building Simulation 2007, Beijing, China

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

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 (81)1196-1211.

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.

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

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

Robinson, D., Haldi, F., Kämpf, J., Leroux, P., Perez, D., Rasheed, A., Wilke, U. (2009), CitySim: Comprehensive micro-simulation of resource flows for sustainable urban planning, Proc. Building Simulation 2009, Glasgow.

Wetter, M. (2004), GenOpt, Generic Optimization Program, User Manual, Version 2.0.0., Technical report LBNL-54199, Lawrence Berkeley National Laboratory, Berkeley, CA, USA.