The 'Deep Blue' Challenge - Human Architects vs. Computer Aided Optimization in the Design of Cost-efficient Building Retrofit

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ABSTRACT: The expert system presented in this paper is able to evaluate the energy performance of buildings and to perform two types of optimization for retrofit design based on Bacterial Evolutionary Algorithms. The cost efficient retrofit finds the best energetic improvement from a given budget, while the energy efficient renovation minimises the retrofit cost for a prescribed target value of the specific heat loss coefficient.

In this paper, the performance of computer-aided optimization is compared to that of human architects or engineers, just like in the famous chess playing experiment. While architects rely on their intuition, knowledge, experience and a limited number of calculation scenarios when designing a building retrofit, the computer has the advantage of a large computing capacity. Strengths and weaknesses of the computational method are discussed through case studies.

Keywords: energy; building; design; retrofit; optimization; evolutionary algorithm

INTRODUCTION

Increasing the energy efficiency of the building sector is crucial to achieve the 2020 goals of the European Union: to reduce energy consumption by 20%, to reduce CO_2 emissions by 20% and to increase the share of renewable energy sources to 20% of total energy consumption by 2020. The building sector, accounting for about 40% of the energy consumption of the EU, provides a great potential for cost-effective energy savings and the reduction of greenhouse gas emissions as shown by various studies. The Fraunhofer Institute and partners [1] show that, by implementing energy saving measures, fuel-use in the EU's building stock can be reduced by 22% (2020) and by 46% (2030) compared to 2005. Ecofys et al. [2] shows that GHGemissions can even be reduced by 44% (2020) and 60% (2030) compared to 2005, when full energy savings are applied in conjunction with renewable energies.

In 2010 the total primary energy consumption of Hungary was 1 085 PJ. About 40% of this energy is consumed by the operation of buildings (434 PJ). Two-thirds of the operational costs are attributed to the heating and cooling of buildings, resulting in an annual energy consumption of 289 PJ. According to the National Energy Strategy 2030 [3], by 2030 Hungary intends to achieve a 30% decrease of this figure. Thus 87 PJ of energy has to be saved by the energetic improvement of the Hungarian building stock. Since the new buildings have to follow high energy standards and the building rate is quite low, most of this energy has to be saved by the appropriate refurbishment of the existing building stock. Approximately 70% of the 4.3 million buildings in Hungary does not conform the modern technical requirements, thus 3 million buildings are potential subjects of refurbishment. The situation is similar in many European countries.

Since the European, national and household resources available for the refurbishment of buildings is quite limited, they have to be exploited in the most efficient, i.e. optimal manner. The refurbishment design of an actual building is a highly complex procedure. Very low energy consumption can be achieved via a large variety of energy saving measures. It is possible to achieve very high energy efficiency by applying thick insulation, high tech windows and complex building service systems with renewable energy sources. However, these measures have their 'price' in terms of investment costs, and also in terms of environmental impacts. In practice, architects and engineers design the so-called 'optimum' retrofit solution of an actual building based on their previous experience, intuition, and possibly based on a limited number of calculation scenarios. Then an option with relatively low energy consumption and acceptable cost is selected.

Clearly, this approach might be quite sub-optimal, i.e. due to the high complexity of the design process the energy saving achieved by the refurbishment might be considerably smaller than the technically possible ideal limit, i.e. the energy saving potential of the particular building. Consequently, part of the refurbishment budget is potentially wasted, while a considerable fraction of the energy saving measures become locked into the building for decades.

In this paper, the ENERGOPT expert system [6] is presented that is a relatively new initiative in the field. The objective of the system is to employ state-of-the-art algorithms [7] to determine the optimal retrofit strategy of a particular building in a short time scale well fitting into modern engineering design cycles. We also present a methodology to measure the performance of human architects against the performance of the automatic optimization tool. Finally, we apply the theory for the analysis of case studies targeting the optimization of retrofit designs by human architects.

The structure of this paper is the following. In section 2 the mathematical foundation of the system is established. Feasible definitions are given to the energy saving potential of a building and to the efficiency of the retrofit designed by human architects. The computation of the optimal retrofit by the ENERGOPT is outlined in section 3. In section 4 the performance of the ENERGOPT system and four human experts are compared on the base of two case studies considering the refurbishment of existing buildings. In section 5 the results are analyzed, the potential fields of applications are highlighted and the focus of future developments is summarized.

MATHEMATICAL FRAMEWORK

In order to establish a solid ground for the analysis and discussion of the results in the context of building optimization, we propose a suitable terminology and the corresponding definitions.

The state vector of a building

Consider a building subject to renovation. From energetic point of view, the actual *state* of the building can be described by a set of numbers reflecting the properties of its components (e.g. thickness of façade wall). Some of these components can be changed during the refurbishment process (e.g. wall insulation), some other components cannot (e.g. in many cases the base area of the building). Note, that it is always case dependent which components are adjustable, i.e. can be changed, modified or replaced. Let us group all quantities describing the adjustable components of the building into a one-dimensional array. We refer to this array as the *optimization state vector of the building* (or simply the state vector) and label it by W. In a simple test case, when the refurbishment can only target the wall insulation and a single window, W has the following 3 components: the type of insulation, the thickness of the insulation and the type of window.

In the context of building optimization three different states of a building have to be distinguished. The *initial state* is the one to be improved by the refurbishment process. The *refurbished state* is obtained by the actually realized retrofit that is designed by human experts. Finally, the *conditionally optimal state* describes an ideal state, corresponding to the technical limitations posed by

- the original characteristics of the building,
- the material costs and salaries,
- the prescribed budget.

We use the phrase *conditionally* to express the fact that typically the retrofit has to obey one or more constraints or conditions, e.g. the total budget of the refurbishment must not exceed a prescribed limit, or the refurbished building has to reach a certain energy quality. The retrofit transforming the initial state to the optimal state is referred to as the *optimal retrofit* or design. Thus, the optimal retrofit expresses the best possible improvement on the initial state without violating the given constraint, e.g. prescribed budget limitation. In principle, no human expert is supposed to design a better state than the optimal state. Note, that the optimal state is in fact *a priori* unknown.

In general, quantities describing the initial, refurbished and the optimal states will be labelled by subscripts I, R and O, respectively. Thus, the corresponding state vectors are labelled by W_I, W_R and W_O, respectively.

The objective function and the measures of retrofit design

Usually, the goal of the optimization of a building envelope is to find state W_O that minimizes a state-dependent quantity defined by the customer. It is referred to as the *objective function* or *fitness functionF*, describing either energetic (e.g. annual heating energy), economic (e.g. annual heating cost) or environmental (e.g. annual CO_2 emission) aspects. Common objective functions are:

- specific heat-loss coefficient: q
- total primary energy consumption factor: EP
- annual heating energy need: Q_H
- annual CO_2 emission: $CO2$
- annual cost of heating.

Since these quantities depend on the state vector and they are not independent from each other, selecting one of them as an objective function is likely to decrease all the others. For the sake of simplicity, let Y label any of the functions listed above. In the followings we define some measures in terms of Y describing the quality of the refurbishment designed by a human expert.

The difference between the initial value Y_I and the optimal value Y_O defines the largest possible improvement in terms of Y, referred to as the *conditional saving potential*:

$$\varphi^Y = Y_I - Y_O.$$

The *efficiency* of the retrofit transforming the initial state to the refurbished state is

$$\varepsilon^{Y} = (\mathrm{Y}_{I} - \mathrm{Y}_{R})/\varphi^{Y} .$$

Observe, that $0 \leq \varepsilon^{Y} \leq 1$ always holds and that the closer the value of ε^{Y} is to unity, the better the human performance is. In an ideal case, i.e. when the human expert finds the optimal solution, $\varepsilon^{Y} = 1$ holds. The quantity

$$\Lambda^{\mathrm{Y}} = 1 - \varepsilon^{Y} = (\mathrm{Y}_{R} - \mathrm{Y}_{O})/\varphi^{Y}$$

defines the *lock-in-ratio* of the retrofit transforming the initial state to the refurbished state in terms of Y. It expresses the relative amount of Y that is locked into the building due to sub-optimal nature of the retrofit designed by a human expert. The closer the lock-in-ratio to unity, the worst the quality of the retrofit is. Clearly, $\varepsilon^{Y} + \Lambda^{\mathrm{Y}} = 1$ always holds.

THE OPTIMAL STATE

In a real retrofit project, the optimum state of the retrofit (W_{O}) is not known and generally cannot be calculated. Architects typically evaluate a number of combinations and select the one with the lowest energy consumption and acceptable costs. Although such a solution is often regarded as 'optimal', it is rarely so either from a mathematical or an energetic point of view. Designing a retrofit is a highly complex process, involving the evaluation of a large number of scenarios based on excessive data sets. Additionally, a subtle balance has to be maintained between the quality of the building's components and the corresponding costs. Other aspects, such as technical and legal limitations are often decisive in a real life project, but in this paper we only focus on the energy performance and the costs, which is already a complex issue in itself.

From mathematical point of view the building optimization is equivalent to finding the global extremum of the objective function defined in a space with as many dimensions as the number of components of the state vector. As an example, consider ten variables in a scenario (e.g. orientation, window ratio, insulation level, heating fuel etc.). In this case, one state of the building is represented by ten numbers, i.e. with a point in a 10-dimensional space. If each of these quantities can take only 20 different values (which is quite a small number compared to practical applications), then 20^{10} different variations of the building exist. Note that in real applications there are much larger problems to handle.

In such cases the tools of applied mathematics must be employed. A large variety of methods exist for finding the optimum. However, most classical treatments based on operational research or combinatorial optimization are unable to handle these problems defined in a 10+ dimensional case. Such problems can be solved by modern optimization techniques based[2] on heuristic approaches (see e.g. [5]). A common feature of these methods is that they are unable to determine the exact optimum. However they can find so-called quasi-optimal solutions approximating the global optimum. These methods have the ability to maintain a user adjustable balance between the goodness of the solution and the CPU time available for the optimization process. In the rest of this paper the optimal state[3] vector will be approximated by quasi-optimal solutions.

The ENERGOPT expert system

The expert system ENERGOPT [6] incorporates state-of-the-art optimization methods superior to most technologies applied so far in this context. The ENERGOPT has a modular structure (Figure 1). The underlying material and salary databases contain the relevant material properties, the cost of the materials and the salaries. The evaluation module calculates the energy performance. The optimization module is based on a novel bacterial evolutionary method [7] well suited to the specific problem formulation in the renovation sector. The basic data of the building must be entered in the computing framework, as required by the evaluation module. The output is a set of optimized parameters describing the optimal state of the retrofit design. The advantage of this modular structure is that any module can be changed or improved without affecting the other modules, as long as the communication interfaces are not changed.

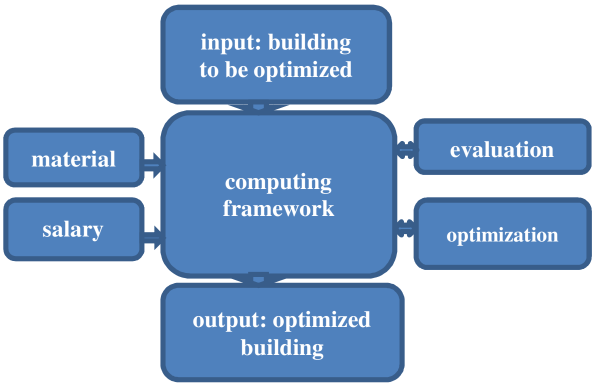

Figure 1: Structure of the ENERGOPT expert system

In its present state, the expert system is able to evaluate the energy performance of buildings according to the Hungarian regulation and to perform two types of optimization. The cost efficient retrofit finds the best energetic improvement from a given budget, while energy efficient renovation seeks the minimum retrofit cost at a given value of the specific heat loss coefficient.

The main advantages of the ENERGOPT system are:

- Instead of applying thermodynamic simulation software, the energetic state of a building is evaluated according to the national building code of Hungary, which is a static method. Thus, the optimization process becomes quite fast. However, it would also be possible to incorporate a dynamic simulation module.
- The interpretation of the results is based on precise definitions of the conditional energy saving potential and the efficiency of a building retrofit.
- The ENERGOPT framework is based on state-of-the-art optimization techniques [7] expressing superior performance over the genetic algorithms frequently employed in recent studies.
- The ENERGOPT has low hardware requirements, it is easily run in parallel environments and it can serve a large number of users simultaneously.

The optimization problem is solved by the ENERGOPT expert system [6] in the following four steps.

1) All data affecting the energetic status of the building are entered into the evaluation module and the energy category of the building is computed.
2) The optimization constraint is set (e.g. the budget is 12 000 EUR).
3) The optimization module evaluates the optimal state of the building.
4) The output is written in the form of an Excel table and some other internal formats containing all physical and cost related information of the components that were modified during the optimization. Additionally, the energetic status of the optimal state is evaluated.

COMPARISON WITH HUMAN ARCHITECTS

In this section the performance of human architects is compared to the ENERGOPT system based on two case studies. The goal is the optimization of the retrofit design. The optimization targets the minimization of the specific heat loss coefficient, q, which includes the transmission heat loss coefficient of the building minus the solar gains per heated volume, expressed in W/m^{3}K. The retrofit has to obey a prescribed budget limitation; here we choose 7 200 EUR.

Note, that this study is not a rigorous statistical investigation based on the analysis of representative data sets. It is a simple comparison based on the work of four experienced architects. Thus, the conclusions do not have general scope. Nevertheless, until a detailed statistical analysis is performed, the usefulness of this limited study is apparent. First, it provides indications on the anticipated saving potential and efficiencies. Second, it reveals the different approaches adopted by the human mind and the mathematical algorithm.

Building 'A'

In the test case we consider the refurbishment of a family house situated in Budapest, built in 1950. The building has two heated floors, with an unheated cellar and an unheated attic. The total heated floor area is $164.64\,m^2$. The specific heat loss coefficient of the original building is $q_I = 1.14\,W/m^3K$, the total primary energy use is $EP_I = 326\,kWh/m^2yr$. The energy category of the building is F on the energy certificate. The source of heating is natural gas.

Building 'B'

The building is an apartment building from 1933 with a total heated floor area of 341 m^2. The building has three heated floors. The third floor is partly a heated attic and partly an unheated roof space. The specific heat loss coeffient is $q_I = 0.65\,W/m^3K$, and the total primary energy use is is $EP_I = 312\,kWh/m^2yr$. The category of the building is G. Every dwelling has its own gas boiler for space and water heating.

In the test computation only the optimization of the building envelope is performed, the heating system is unchanged. There are four different types of opaque building envelope elements (façade walls, attic, cellar floor, attic floor), five types of windows and two doors optimized in building 'A', and the same opaque elements, four types of windows and a door in building 'B'. Thus, the problem is equivalent with finding the optimal solution in a 11 and a 9 dimensional search space for building 'A' and 'B', respectively.

Four architects/engineers participated in the test, all experienced in the field of building energetics. First, the energetic status of the original building was evaluated by the energetic evaluation module and the energy category was determined.

In the second phase the retrofit of the envelope is designed by the architects under three conditions. First, the architect has to spend eight working hours with the design of the retrofit strategy. In this phase the only goal is to decide which building envelope elements to insulate and with what type of insulation, and what type of windows to install for replacement. The second condition is that the total budget of the renovation must not exceed 2.1 million HUF (7 200 EUR) in building A, 4 million HUF (13 800 EUR) in building B. The renovation budget includes the costs of the built in materials and the salary of the workers. The third condition is that all technical and pricing information is obtained from an existing database, i.e. the expert can only select from the available components.

In the third phase, all structural data of the original building is fed into the optimization module of the ENERGOPT system and the same total budget is set as a constraint. The optimization process is performed in less than 20 seconds on a laptop equipped with Windows 7 operating system and an Intel core i5-450M CPU working at 2.4 GHz clock speed.

Table 1: Initial, refurbished and optimized results for building ‘A’, indicating the conditional saving potential

	cat.	q (W/m^3 K)	Q_H (kWh/yr)	total heating cost (EUR/yr)	total CO_2-em. (kg/yr)
initial	F	1,14	43508	2754	10828
refurb v1	D	0,48	19396	1476	5933
refurb v2	D	0,48	19382	1475	5930
refurb v3	B	0,30	16129	1303	5270
refurb v4	B	0,35	17599	1381	5568
optimized	B	0,29	15586	1274	5159
saving potential		0,85	27922	1480	5668

Table 2: Efficiency of the human design for building ‘A’

	q (W/m3K)	QH (kWh/yr)	total heating cost (EUR/yr)	total CO2-em. (kg/yr)
v1	78%	86%	86%	86%
v2	78%	86%	86%	86%
v3	99%	98%	98%	98%
v4	93%	93%	93%	93%

Table 3: Initial, refurbished and optimized results for building ‘B’, indicating the conditional saving potential

	cat.	q (W/m^{3}K)	Q_H (kWh/yr)	heating cost (EUR/yr)	CO_2-em. (kg/yr)
initial	G	0,65	89401	5457	21449
refurb b1	C	0,14	28914	2251	9170
refurb v2	C	0,14	28481	2228	9082
refurb v3	D	0,14	30424	2331	9477
refurb v4	D	0,13	30593	2340	9511
optimized	B	0,12	26386	2117	8657
saving pot.		0,53	63015	3340	12792

Table 4: Efficiency of the human design for building ‘B’

	q (W/m^{3}K)	Q_H (kWh/yr)	heating cost (EUR/yr)	CO_2-em. (kg/yr)
v1	96%	96%	96%	96%
v2	96%	97%	97%	97%
v3	96%	94%	94%	94%
v4	98%	93%	93%	93%

The energy category of the building and other relevant quantities are presented in Table 1 and Table 3 for the initial, refurbished (human design) and the optimal (ENERGOPT design) states. The conditional saving potentials of the initial state and the lock-in-ratios of the retrofits designed by four human experts are presented in Table 2 and Table 4.

The results confirm the expectations, i.e. the ENERGOPT provides better results with respect all quantities. For building A the annual delivered heating energy need is on average 2540 kWh less, the savings on the annual heating (space and water) are 135 EUR and the CO_2 emissions are 516 kg less. The efficiency of the human retrofit was on average 90 %, resulting in 10 % of locked in heating energy saving potential, CO_2 emission decrease potential and cost saving potential. In case of building B, the architects’ design was more efficient than for building A, resulting in only about 5% lock-in potential on average. However, due to the larger dimensions of the building, the lock-in potential is higher when considering the absolute values. The difference in energy categories between the architects’ and the optimized design is two in certain cases (cat. D and B).

For building ’A’ the best strategy was to insulate well the opaque elements, as the largest part of the heat losses was due to these elements, and spend only the remaining budget on costly window replacements. This strategy was followed by ’architect 3’ and also by the ENERGOPT system.

The human results may seem rather good at first sight, however note the followings. The buildings are rather simple, with a relatively low variety of retrofit strategies. Moreover, the current version of the database is quite limited, and contains only a relatively small number of insulation products and windows. In real life applications, it is not expected that human experts would achieve such a high efficiency.

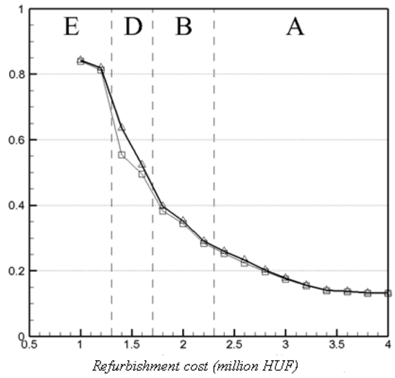

Figure 2: ENERGOPT optimized results for different refurbishment budget costs (building A) in units of million HUF.

CONCLUSIONS

The optimal retrofit design is undoubtedly an essential component of sustainable refurbishment of buildings. The ENERGOPT expert system is a state-of-the-art research tool supporting architects in the exploitation of the available financial resources at their highest extent. In two case studies we performed the optimization of existing building envelopes. The goal of the optimization is to minimize the specific heat loss coefficient by not exceeding the prescribed cost limitations. This task was performed by four human experts and also by the ENERGOPT system. Compared to the human expert, the ENERGOPT designed a retrofit resulting in a building with lower q and EP values, and significant savings in energy, CO_2-emissions and costs. While it is not debatable that every building is unique, and the final choices of engineers are influenced by many factors beyond energy efficiency, such a tool can prove to be very useful in assisting the design process. The quality of the results strongly depends on the underlying databases.

Apart from providing superior results, the ENERGOPT has other attractive benefits. It is a fully automatic system, always finding a quasi-optimal solution with practically zero-lock-in potential in less than 60 seconds for a building of average complexity. For an architect, it may take several hours or days to calculate the achievable savings for different renovation budget limitations in a complex case.

The ENERGOPT system has a wide range of potential applications. First, it provides a viable tool to maximize the cumulated heating energy savings for the life cycle of buildings. If the Hungarian building stock were fully refurbished, on national levels the cumulated savings would reach at least 0.1 billion EUR/annum extra compared to the refurbishment based on the design of human architects with about 80% efficiency.

The ENERGOPT could also be used to measure the efficiency of actual retrofit design proposals before granting permissions from the authorities. In case of insufficient efficiency, the system automatically provides suggestions to the human expert to improve his/her design. This idea could be well disseminated by the banking sector. Indeed, the potential hazard of the bank providing the loan for refurbishments can be substantially decreased if the refurbished building has better quality and saves more money for its users.

Finally, the objectives of European national energy strategies regarding the decrease of energy consumption of buildings can be fulfilled more economically. Indeed, these strategies prescribe a targeted decrease of cumulated heating energy for the coming decades. By exploiting the capabilities of the ENERGOPT system the same goals can be reached from a substantially smaller national budget.

Perhaps the most exciting future development is the generalization of the concept of conditionally saving potential. It has a prospective application in determining the optimal budget that should be spent on the refurbishment of a particular building. When the budget reaches a certain threshold, its additional increase might not be justifiable by the eventually decreasing energetic improvements. From the other hand, in a case of too small budget the general energy saving potential of the building might not be fully exploited by the cheap refurbishment. Further important development could be the localization of the system to other European countries and to investigate its benefits under different regulations.

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