COMBINED ENERGY SIMULATION AND MULTI-CRITERIA OPTIMISATION OF A LEED-CERTIFIED BUILDING

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ABSTRACT

The target of the described study was to gain some experience in applying combined energy simulation and multi-criteria optimisation to a real building which was going to be LEED-certified. The building is a two-storey shopping centre. For energy simulations a model of the building was created. The simulation tool used was IDA-ICE, which is a software accepted for LEED energy simulation. The simulation program was combined with an in-house implemented Pareto-archive NSGA-II algorithm. Two objective functions were used: first the amount of yearly purchased energy and second, the investments related to the design variables. Optimisation using a detailed LEED energy simulation model is computationally expensive for a large building. However, developing the approach further and integrating it to the planning process definitely offers huge possibilities.

INTRODUCTION

Building certification is becoming more common in all building sectors. It is a mean to improve energy efficiency and to reduce their environmental impact. Energy aspects play an essential role in practically all certification procedures. Leadership in Energy and Environmental Design (LEED) is a rating system for the design, construction and operation of high performance green buildings. Developed by the U.S. Green Building Council (USGBC), LEED is intended to provide building owners and operators a concise framework for identifying and implementing practical and measurable green building design, construction, operations and maintenance solutions. In this context the relevant approach is LEED for new constructions (USGBC 2012). It gives points for different features of the building such as site, water efficiency, energy and atmosphere etc. The Energy and Atmosphere criteria account for a maximum of 35 out of 110 points.

The energy efficiency of the planned building has to be shown in the LEED process by simulation. Only simulation programs accepted by USGBC can be used. There are numerous variables, which affect the energy demand and efficiency of a building. If the goal is to find the best ones amongst all possible combinations, it could take millions of simulations. Combining simulation with optimisation drastically reduces the need for simulated cases.

Wright (Wright et al. 2001) was one of the first to combine building simulation with an effective search optimisation method, the Genetic Algorithm (GA). Wang (Wang et al., 2005) started to apply building optimisation under the title “green building design”. There are more recent published optimisation exercises focusing on the material selection of a LEED building (Castro-Lacouture et al., 2009) and the use of BIM (Barnes et al., 2009).

Real optimisation is often quite troublesome to integrate in the building design process. It needs re-evaluation and unprejudiced attitude. The target of this study was to gain some experience in applying combined energy simulation and multi-criteria optimisation to a real building, which was going to be LEED-certified.

THE CASE STUDY BUILDING

The case study building is a two-storey shopping centre located in Jyväskylä, Finland, latitude 62.23 N, longitude 25.73 E. It contains a large supermarket, several smaller shops and two restaurants. The total floor area is 22000 m^2. The main part of the building is on one level with a ceiling height of 7 metres. A general view of the building is shown in Fig. 1.

The wall construction is a common steel-mineral wool-steel construction: steel 0.005 m, mineral wool 0,163 m, steel 0,05m. There are windows on the South and East walls but not in the supermarket section because natural light must be avoided in spaces for groceries. The floor plan is quite fragmented and complicated because of the many shops that are present.

There is a VAV air-conditioning system in the main part of the building. The controls depend on the indoor temperature and concentration of CO_2. Minimum air flows are 50% lower than the maximum flows. Night cooling is used in the supermarket and the shops. Heat generated by the supermarket refrigeration systems is used in pre-heating of ventilation air.

Fig. 1 General view of the building

The building is heated with a district heating system. Heat is delivered by a hydronic system. Cooling is partly achieved via air transfer, partly via cooling beams.

Lighting in the building is implemented with normal fluorescent lamps except in one of the shops where LED lamps are used. The lighting energy demand is 25 W/m^2 in the market and 10-20 W/m^2 in other parts of the building. Lighting is automatically controlled according to the usage time. The total energy demand of the baseline building is 142 kWh/m^2, of which 53 % is for lighting purposes.

ENERGY SIMULATION

Simulation in LEED

Simulation in LEED can be divided into two stages. The proposed building is first simulated according to the planned building, including all zones, HVAC equipment and construction details. Actual schedules and heat loads are used.

In the second stage, a baseline building is constructed based on the proposed building model. The baseline building is fitted with ASHREA 90.1 standard values, but using the same schedules and heat loads as the proposed building. A one-year simulation is run for the proposed building. Four one-year simulations, with four orientations, are run for the baseline building. Results for the energy consumption and costs are calculated for each energy source and according to their prices. The difference in the energy costs determine how many LEED points are awarded to the project.

LEED requires that the simulation program is approved by the rating authority and has the ability to at least explicitly model the following: 8760 hours per year; hourly variations in occupancy, lighting power, miscellaneous equipment power, thermostat set points and HVAC system operation, defined separately for each day of the week and holidays; thermal mass effects; ten or more thermal zones; part-load performance curves for mechanical equipment; capacity and efficiency correction curves for mechanical heating and cooling equipment; air-side economisers with integrated control; baseline building design characteristics.

In general, the simulation program must be capable of performing design load calculations in accordance with generally accepted engineering standards and handbooks. In addition, the simulation program has to be tested according to the ASHRAE Standard (ASHRAE 2007). It is also recommended that the simulation program uses hourly climatic data in several well-known formats, such as ASHRAE IWEC and EPW.

Simulation software

IDA Indoor Climate and Energy was used (IDA ICE 2012) as the simulation tool. It is a whole-year detailed and dynamic multi-zone simulation application for study of thermal indoor climate as well as the energy consumption of the entire building. It has a general-purpose variable time step solver, which automatically adapts to the nature of the problem. Modelling is based either on the Modelica language or on the Neutral Model Format (NMF). The software is validated according to the most common simulation software validation procedures (ANSI/ASHRAE 140-2007, EN 15255, EN 15265).

Practical aspects in implementation of simulation

There were several practical problems in the simulation because of the large size and complex structure of the building. The modelled building was one of the first ones modelled for LEED certification in Finland. The requirements for modelling were stricter than in the previous modelling practice by Skanska.

Some practical problems in keeping the zone temperatures at appropriate levels were related to modelling the VAV- air-conditioning system. Also, collecting all the up-to-date input data from all of the actors in the design process was extremely time-consuming. Moreover, there were some problems in importing the IFC-model to the simulation program.

In the phase where the building body was divided into zones, some slight simplifications were done to keep modelling and simulation times reasonable. Not every room or corner was modelled like in the actual building and changes in height in the same zone were discarded. Of course the model should describe the building well enough to produce results representing the energy consumption in a reliable way. Finally, one-year hour-by-hour simulation took around 75 minutes using a computer with a 1.83 GHz dual core CPU.

When the model was combined with the optimisation tool, some effort was required to find a working method for communication between the simulation program and GenOpt. Also, the right combination of meaningful decision variables to reduce the energy consumption or the construction price was not straight forward.

OPTIMISATION

Problem definition

The optimisation problem is defined as a multi-objective problem by choosing two conflicting objectives and trying to minimise them simultaneously. The objective functions in this case are the energy savings and the investment cost. The formal definition is

$$Min\{F_1(\boldsymbol{x}), F_2(\boldsymbol{x})\} \quad (1)$$

so that

$$H_T \leq 300\ Kh \quad where$$

$$H_T = \sum_0^{8760} (T_i - 24)\,\Delta t \quad when\ T_i > 24\ °C \quad (2)$$

$$H_T = 0 \quad when\ T_i \leq 24\ °C$$

and

$$\boldsymbol{x} = (x_1, x_2, \ldots, x_n)^T. \quad (3)$$

The objective function $F_1(\mathbf{x})$ is the savings of purchased energy compared to the baseline building. The objective function $F_2(\mathbf{x})$ is the additional investment cost of energy efficiency improving measures compared to the baseline building. The constraint H_T gives the maximum allowable number of degree-hours of the indoor air temperature T_i exceeding the 24 °C limit during the load hours of a year, according to LEED demands. Finally, vector $\mathbf{x}$ contains all of the decision variables of the problem. In this case there were seven discrete variables, which are shown in Table 1. The total number of combinations is 972.

Table 1 Decision variables

variable	value 1	value 2	value 3	unit
Roof				
U-value	0.162	0.149	0.093	W/m2K
add. cost	0.00	1.35	11.78	€/m2
Floor				
U-value	0.242	0.185	0.123	W/m2K
add. cost	0.00	5.00	15.00	€/m2
Wall				
U-value	0.23	0.17		W/m2K
add. cost	0.00	2.70		€/m2
Window				
U-value	1.1	1.0	0.85	W/m2K
SHGC	0.51	0.53	0.48	-
ST	0.43	0.34	0.29	-
add. cost	0.00	12.93	30.37	€/m2
Daylight-linked lighting controls (not in the supermarket)				
additional cost			6.18	€/m2
Night ventilation				
starting	21	22	23	hour
ending	6	7	8	hour

The U-values are according to real steel-construction alternatives and the corresponding prices are from steel construction providers. For wall insulation thickness the provider had only two alternatives available because of the standardised dimensions of the steel construction. Window alternatives are commercial products as well. Besides U-values, solar heat gain coefficient (SHGC) and solar transmittance (ST) values were also used in the simulation. Lighting was either controlled according to the usage time or to the time combined with daylight control. Night ventilation had three alternative options for its starting time and three more for its ending time, which could be combined independently. These times were chosen according to people's estimated time of arrival and of departure. Since night ventilation is implemented by the building automation system, it has no investment cost.

Optimisation tools

In this study an in-house variant of the well known NSGA-II algorithm (Deb et al. 2002) was used. The algorithm is called Pareto Archive NSGA-II. The main difference between the original NSGA-II and the Pareto Archive NSGA-II is that the Pareto Archive NSGA-II has an unconstrained archive of elite solutions. NSGA-II algorithm implements elitism by maintaining two populations of size N: the adult population P from the previous generation and the children population Q, from the current generation. At each generation these populations are combined and sorted according to level of domination. Then N solutions are selected as the next adult population P. The number of non-dominated points available after sorting may be greater than the population's size N, which defines the number of (elite) points that are kept by the NSGA-II algorithm. When the number of non-dominated points available is greater than N, NSGA-II selects the N least crowded solutions by using the crowding distance measure. The rest of the non-dominated points, if any, are rejected. In the Pareto Archive algorithm, non-dominated points that would be rejected are saved into the archive and are used in the following generations as possible parent solutions.

The Binary Genetic Algorithm encodes decision variables as variable length bit strings. These bit strings are then combined to form the chromosome that represents the solution. A Point generating mechanism of the binary GA operates with the encodings of the solutions rather than with the decision variable values directly. In this study a two-point crossover and bit-wise mutation operators were used as the point generating mechanism.

Combining simulation and optimisation

The implemented Pareto Archive NSGA-II multi-objective algorithm was used within the GenOpt framework (GenOpt 2011)_to reduce the tasks related to integration of simulation and optimisation. GenOpt is an optimisation environment for minimisation of a cost function that is evaluated by an external simulation program. GenOpt has an algorithm interface that allows adding new optimisation algorithms, without knowing the details of the program structure.

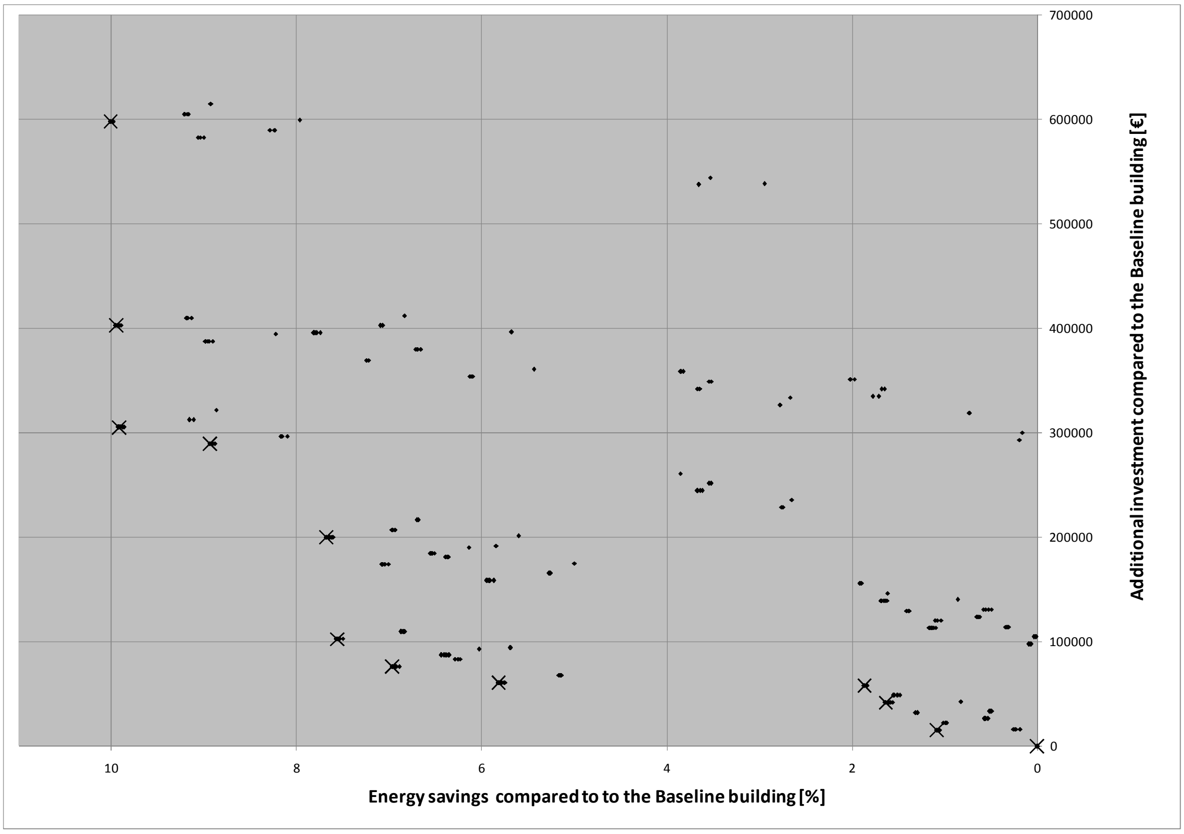


Fig. 2 All individuals (266) of the optimisation run. Non-dominated solutions marked with a cross.

The kernel of GenOpt reads the input files, calls the simulation program, stores the results, writes output files, etc. The algorithm developer has to deal only with optimisation algorithm related tasks, while GenOpt deals with the rest of the tasks. Because the simulation was very time-consuming, the population size was only ten individuals. The cross-over probability was 0.8 and the mutation probability was 1/(number of bits of the individuals).

RESULTS AND DISCUSSION

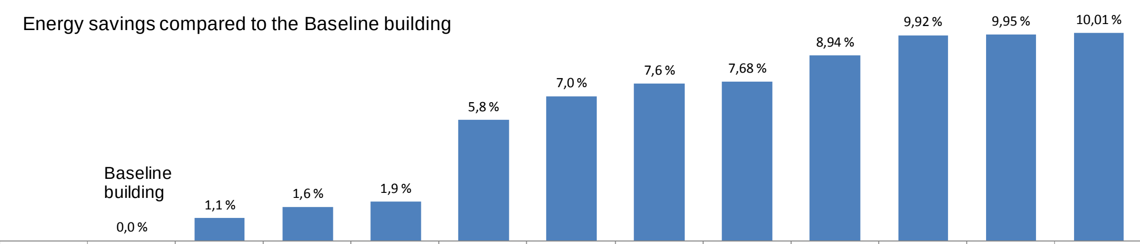
Optimisation results

All 266 results of the optimisation run are shown in Fig. 2. The non-dominated solutions are marked with a cross. Further details regarding the non-dominated solutions are shown in Table 2.

Fig. 2 shows a relatively sparse Pareto front. Also, the solutions seem to have gathered into a few large clusters as well as several mini-clusters. In the vicinity of each non-dominated solution is a mini-cluster of dominated solutions.

Table 2 shows that all solutions use maximal period for night cooling. Most of the solutions have lowest quality windows with U-values of 1.1 W/m²K. Most solutions are also using daylight control. U-values of structures have mixed combinations. However, solutions with best insulation levels are the most expensive ones. Energy savings, compared with the baseline building, were between 1 and 10 % and the corresponding additional investments 0.71 – 27 €/m2

Table 2 Details of the non-dominated solutions



Payback time [a]	0,00	4,11	7,33	8,95	3,00	3,15	3,90	7,49	9,32	8,84	11,63	17,17
Additional investment [€]	0	15595	41836	58157	60843	76439	102679	200346	289815	305410	403077	598412
Ending night ventilation	8:00	7:00	7:00	7:00	7:00	7:00	7:00	7:00	7:00	7:00	7:00	7:00
Starting night ventilation	21:00	21:00	21:00	21:00	21:00	21:00	21:00	21:00	21:00	21:00	21:00	21:00
U-value window [W/m2K]	1,1	1,1	1,1	0,85	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1
Lighting control	usage time	usage time	usage time	usage time	daylight control	daylight control	daylight control	daylight control	daylight control	daylight control	daylight control	daylight control
U-value floor [W/m2K]	0,242	0,242	0,242	0,242	0,242	0,242	0,242	0,185	0,242	0,242	0,185	0,123
U-value roof [W/m2K]	0,162	0,162	0,149	0,149	0,162	0,162	0,149	0,162	0,149	0,149	0,149	0,149
U-value wall [W/m2K]	0,23	0,17	0,17	0,17	0,23	0,17	0,17	0,17	0,23	0,17	0,17	0,17

Discussion

Because of the computationally very expensive simulations and thus small populations, the approach leads to a rather sparse Pareto-front. Nevertheless, there were enough results to get a sufficient selection of non-dominated solutions and to find some of the best alternatives. The energy savings were modest because many of the most important decision variables were already fixed, thus giving no possibility to utilise the whole optimisation potential. For example, better utilisation of daylight using more windows or alternatives for more efficient electrical lighting arrangements would have given better results as the share of lighting energy was more than 50% of the total energy demand.

The optimisation algorithm did cover the whole solution space well by finding some of the extreme solutions as well as the intermediate ones. However, it was not able to produce a Pareto front with even distances of non-dominated solutions. Instead, the solutions seem to form few large clusters and tens of mini-clusters. The reason for this might be that after 24 generations, the algorithm had already located each of the non-dominated solutions in the final result. Since all of the decision vectors of the non-dominated solutions have similar features, the crossover operation applied to these solutions hardly creates new solutions. Instead, with high probability, duplicate solutions are created. Since the population size used in this optimisation run was ten, the solutions selected for mating after generation 24 are the ones that are non-dominated. In a way, the algorithm got stuck, probably in the local Pareto-front. Since the crossover operation is mostly responsible for the search operation of the GA, it is expected that after generation 24, the algorithm could not make big changes to existing non-dominated solutions.

It is clear that after generation 24 most of the solutions in the larger clusters were already created. This probably implies that solutions in the larger clusters were the parents of the non-dominated solution(s) in the same clusters. A closer look at the parameters of the mini-clusters show that the decision variables of the individuals in the cluster are similar, except different combinations of night ventilation starting and ending times. For this reason the cost has the same value and the differences in energy saving is also very small.

Mutation probability used in the optimisation run was 1/L, where L is the number of bits used to represent each of the solutions. Since the mutation operation was responsible for the search operation of the GA after the generation 24, higher mutation probability could have been used. However, it is unclear what would have been the effect on the convergence of the algorithm with larger mutation probability.

CONCLUSIONS

From this computational exercise, it can be concluded that the optimisation should be done in an earlier stage of the planning process to influence the major parameters affecting energy efficiency. Too many factors were already fixed and the impact was rather scarce. Optimisation using a detailed LEED energy simulation model is time-consuming for large buildings like the shopping centre. Because of the computationally expensive simulations and thus small populations, the approach leads to a rather sparse Pareto-front and some clustering of the individuals. Other reasons for clustering were probably in the low crossover and mutation probabilities.

However, developing the approach further and integrating it to the planning process definitely offers huge possibilities. For example, a simpler model of the building could be used for preliminary optimisation. Then the full LEED model could be built on this simple model to carry out the final analysis.

NOMENCLATURE

Δt, time increment;

$F_i(x)$, objective function;

H_T, degree-hour constraint;

T_i, indoor air temperature;

x, decision variable.

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