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USING WHOLE BUILDING SIMULATION MODELS AND OPTIMIZING PROCEDURES TO OPTIMIZE BUILDING ENVELOPE DESIGN WITH RESPECT TO ENERGY CONSUMPTION AND INDOOR ENVIRONMENT

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ABSTRACT

Even though simulation is being increasingly used in design of modern buildings, the full potential of simulation is usually not achieved. To improve building and HVAC system performance, designers usually guess different values of design parameters and then redo the simulation without actual knowing if the guessed value will lead to improvement. This is inefficient and labor intensive. In addition, if the number of design parameters being varied exceeds two or three, the designer can be overwhelmed in trying to understand the nonlinear interactions of the parameters. However, techniques exist that allow automatic, multidimensional optimization of a simulation model, leading to better design with less effort.

In this paper, we describe how an optimization can be done using the generic optimization program "GenOpt" and the simulation program "EnergyPlus". In our case study, the optimization yields 22 % energy savings related to the actual design energy consumption. The measures found by using optimization not only decrease operating costs, but also lead to better daylight usage and thermal comfort, which results in higher comfort for the building occupants

INTRODUCTION

The global demand for more sustainable development has resulted in an increasing number of new technologies and design strategies aimed at improving buildings with respect to a variety of performance considerations, such as energy, comfort, cost, aesthetics, environmental impact, etc. As the number of design and technological options increases, so does the complexity and the cost of deciding which combination that is most useful for a given design. Informed decisions require the management of huge amounts of information about the combinations and their performance. Manual management methods are almost impossible to use.

As a method of information management in the design process of energy efficient buildings, the use of Whole Building Simulation Models are being increasingly used. However, the potential of these simulation programs are usually not achieved to the full extent. The interaction between design features, climate, occupants, HVAC and electrical systems in a building is highly complex, and only by resorting to simulations is it possible to understand all the factors involved in the process. Simulations are normally used in a scenario-by-scenario base, with the designer generating a solution and subsequently having the computer evaluating it. This is however, a slow and tedious process and typically, only a few scenarios are evaluated from within a large range of possible choices. In order to improve the design, the designers usually have to guess different values of the design parameters and then redo the simulation without knowing if the guessed value really will lead to improvement. In addition, if the number of design parameters being varied exceeds two or three, the designer can also be overwhelmed in trying to understand the nonlinear interactions of the parameters.

The objective of this paper is to go a step further in integrating the computer media in the design process by making use of it not only as a simulation tool, but also as a design optimization tool. Using automatic, multidimensional optimization techniques, the computer can automatically generate and evaluate possible design improvements and presents the designer with optimal or near-optimal solutions for the problem under study.

To perform optimization we can use optimizing program that can automatically read output files and generate input files for use in simulation programs. The generated input files are based on templates for the particular simulation program. The optimizing program then launches the simulation program, reads the function value being minimized from the simulation result file, checks possible simulation errors, and then determines a new set of input parameters for the next run. The whole process is repeated iteratively until a minimum of the function is found. If the simulation problem has some underlying constraints, they can be taken into account either by a default implementation in the

Class definition of GenOpt[1] or by modifying the function that has to be minimized.

In our case study, we show how optimization can be done using the generic optimization program GenOpt and the simulation program EnergyPlus[2]. In the case study, we use these programs to redesign the building envelope of an existing small school building in Trondheim, Norway, such that a weighted sum of heating, cooling, and lighting energy and PPD value is minimal with respect to the selected design parameters and with highest possible thermal comfort.

In a new design process, the same method can be applayed by using the early-proposed architectural design as the actual values and initial values.

METHODS

Optimizing

An optimization problem consists of (Wetter; 2002):

1. A set of free parameters (the independent variables, also called design parameters).
2. Some constraints that bound the domain of the free parameters and dependent variables.
3. An objective function (the function to be minimized) that depends on the free parameters.

Without loss of generality, optimization can be considered as minimizing a function since maximization can always be translated into minimization by simply changing the sign of the objective function.

Most optimization problems can be formulated as nonlinear constrained problems (Walsh; 1975). However, it is advisable - and in some cases even necessary - to take advantage of some properties of the problem. It is obvious that:

a) no optimization algorithm works best on all possible functions and,

b) no optimization algorithm can guarantee to find the global minimum if local minima exist.

The selection of the optimization algorithm depends primarily on the following considerations:

- structure of the function (linear, non-linear, convex, continuous, number of local minima, etc.)
- availability of analytic first and second derivatives
- size of the problem (number of independent parameters)
- problem constraints (on the independent parameters and/or the dependent variables)

The need to select an algorithm that works efficiently on a particular problem leads to a large number of available optimization methods. We have to bear in mind that there is no general optimization algorithm that works efficiently on all problems.

Convexity is the key point of optimization. If the objective function is not convex or if the feasible domain of the free parameters is not convex, then there is no guarantee that the global rather than a local minimum will be found. However, finding a local minimum is still a better solution than doing no optimization at all.

In our case study, we have used the Hooke-Jeeves algorithm (Hook and Jeeves; 1961). This algorithm moves efficiently along the valley of the objective function and thereby reducing the dimensionality of the problem. This algorithm is efficient for data fitting and since it does not require derivatives, it is also assumed to be a good choice if the objective function is expected to have some discontinuities.

GenOpt

GenOpt is a generic optimization program for multidimensional minimization of an objective function that is computed by an external program (Wetter; 2001). GenOpt automatically finds the values of selected free parameters (the independent variables) that minimize the objective function. GenOpt can be coupled to any simulation program that reads its input from one or more text files and writes its output (i.e., the value of the objective function) to a text file. It is designed for finding the values of user-selected design parameters that minimize a objective function, such as annual energy use, peak electrical demand, or predicted percentage of dissatisfied people (PPD value), leading to best operation of a given system.

EnergyPlus

EnergyPlus is a new building performance simulation program that combines the best capabilities and features from BLAST and DOE–2 along with new capabilities (LBL; 2001). Developed using the heat balance based load calculation algorithm found in IBLAST (a research version of the BLAST program), it consists of new Fortran 90 code that was either created specifically for EnergyPlus or that was reengineered from one of the legacy programs. EnergyPlus is primarily a simulation engine. One of the reasons for this is the broad range of potential users the program might end up having. While each type of user requires the same calculation to be performed, each will have different

[1] HTTP://GUNDOG.LBL.GOV/GO/INDEX.HTML

[2] HTTP://WWW.EERE.ENERGY.GOV/BUILDINGS/ENERGY TOOLS/ENERGYPLUS/

knowledge levels, skills, and goals. Thus, the simulation engine can be the same for all users but the interface to the simulation program will likely be very different.

Construction of the Objective Function

Before we go into the optimizing process, we first have to decide how to summarize different energy forms used for heating, cooling and operation of buildings. There are two forms of energy used in this context: thermal energy and electric energy. The division between use of thermal and electric energy in buildings are on a more general level the division between work and heat. In modern buildings, electricity corresponds to work and heat corresponds to the different type of fuels such as natural gas, oil, wood, or district heating. In some countries it is common to summarize energy consumption of the different energy forms into a total sum or total use of primary energy by giving the different energy forms different Primary Energy Factors (PEF) (Jagemar; 1996). Thermal energy or heat energy, is in this context defined with PEF = 1 and defined as primary energy.

The size of the PEF can be a hot topic for discussion since the size has great influence on what kind of energy source that is most economical for heating and cooling of buildings. One way to decide the size is to use the actual price ratios of the different fuels. The PEF should also reflect the environmental impact of electricity production. In Norway, it is not common to use primary energy factors when adding different energy forms. This is mainly because until recently all electric energy produced and consumed in Norway was based on hydropower, and regarded as primary energy. Since Norway in the near future will use more and more electric energy produced in countries with thermal power stations, it would be natural to use primary energy factors when adding different energy forms. In our example, electricity is therefore multiplied with a PEF of 3.0. This means that electric energy is weighted three times more than thermal energy. In this context, it is important to be aware that the specific energy consumption when PEF's are used is specific primary energy not specific electric energy. This can be confusing since this specific energy consumption is far greater than normal used key figures of specific energy consumption.

The annual source energy consumption is given by:

$$f(x) \triangleq E_{tot} = \frac{Q_{heating}}{\eta_{heat}} + \frac{Q_{cooling}}{\eta_{cool}} + e_{el}(E_{light} + E_{equip}) \quad (1)$$

where $Q_{heating}$ and $Q_{cooling}$ are the zone's yearly heating or cooling energy demand, E_{light} and E_{equip} is the zone's electricity consumption for lighting and equipment. The efficiencies η_{heat} and η_{cool} are typical Net Plant Factors that relate the zone load with the source energy consumption for heating and cooling generation. The Net Plant Factor accounts for the thermal efficiencies of the boilers, furnaces, chiller, cooling towers, and the energy expended by their associated fans and pumps. The Net Plant Factor attempts to give an overall efficiency of the heating and cooling plant by including all the energy expended, with a source-to-site multiplier of 3 for electricity. Net Plant Factors in commercial buildings average 0.44 ($\eta_{heat} = 0.44$) in heating and 0.79 ($\eta_{cool} = 0.79$) in cooling (Huang and Franconi; 1999). Lighting electricity (as well as electricity for fans and pumps) is weighted by a factor of 3, e_{el}, to convert site electricity to source fuel energy consumption.

To ensure that optimizing the annual source energy consumption not aggravate the thermal comfort, we have chosen to use the PPD[3] index as a weighting function. The PPD index is a quality measure of the indoor thermal environment. One certain quality – defined by an acceptable PPD value – can be chosen for a thermal zone. The corresponding PMV[4] range can then be calculated using the following equation (Clarke; 1985):

$$PPD = 100 - 95 \cdot \exp(-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2) \quad (2)$$

Using EnergyPlus, we can calculate the average PMV index for each defined zone (Fanger; 1967; LBL; 2001). By using this average PMV index and equation (2) , the weighting function can be given by:

$$T_g(g(PPD)) = A \cdot (PPD - 5)^m \quad (3)$$

To ensure that the weight is high enough, the constant A is set to the value of E_{equip}. A reasonable value of the exponent was harder to determine. With a little bit trail and error, we found that a value of four gave the desired high penalty. By using (1) and (3) the objective function used in the optimizing process can be stated as:

$$f(x) \triangleq E_{tot} = \frac{E_{heating}}{0.44} + \frac{E_{cooling}}{0.79} + 3 \cdot (E_{light} + E_{equip}) + E_{equip} \cdot (PPD - 5)^4 \quad (4)$$

The calculated PPD value is not added to (4) during night time, since this would reduce the energy savings potential of reduced zone air temperature during night-time.

3 PPD = PREDICTED PERCENT DISSATISFIED

4 PMV = PREDICTED MEAN VOTE

CASE STUDY

The small school building was designed using the CAD-program VectorWorks[5]. The drawing files were saved in DWG file-format. These files were imported in Visio 2002[6], reformatted with height information added. The files were then saved in IFC-format, imported and reformatted trough use of the EnergyPlus IFC client (Karola, Lahtela, Hanninen, Hitchcock, Chen, Dajka and Hagstrøm; 2001). The time consumption for setting up the building model by using this method was approximately 2 hour.

The school building is located at the outskirts of Trondheim city center. The normal to the north facade deviate with 5° related to true north. The exterior wall, roof, floor etc. are constructed of typical material items used widely in Norway. Interior walls are constructed of light materials (plasterboard). The building has four classrooms connected to one common area. Total area is 461 m^2. The building is equipped with one ventilation system and one hydronic heating system.

There are approx. 22 pupils in each classroom, giving a total of 92 persons (including the teachers) in the building at the same time. The lighting effect is set to 13 W/m^2 in the classrooms. In each classroom, there are four PC's. All windows have exterior shading device. The shading device is actuated only during summer and when the solar irradiation on the window exceeds 200 W/m^2. The zone has daylight controls with an illuminance setpoint of 500 lux at two points 3 m from the windows. The temperature setpoint are 24 °C in the summer and 22 °C in the winter. The air changes per hour is based on the design criteria class 2 (normal expectation to the IAQ), in the Norwegian Standard NBR F 154/2001. Since the IAQ is of great importance to the learning environment, the air changes per hour are not used as a design parameter in the optimizing process. The ventilation schedule is based on 100% fresh air in working hours (7:30 – 17:00). In non-working hours (17:00 – 7:30) the ventilation system is turned off.

In the case study, we have chosen to vary fourteen design parameters under the optimizing process (see table 2). These are windows area (north, south, east and west), windows type (north, south, east and west), thermal mass, exterior wall insulation thickness, roof insulation thickness, floor insulation thickness, shading device transmission and night setback temperature. In connection to each design parameter, there is defined one specific start value, one specific minimum value, one specific maximum value and a step value. The step value is a GenOpt variable used to scale the design parameter.

Usually, both window height and width can be varied. In our case study, the width and number of window are fixed due to architectural circumstances. The height can only be varied. In the optimizing process, we chose to vary the height from floor to lower window frame with the values shown in table 2. The topmost window frame is fixed at 2.1 m above the floor. The energy effect of the varying window area at different facades is shows in figure 1. The height from floor to lower window frame is the only varied parameter.

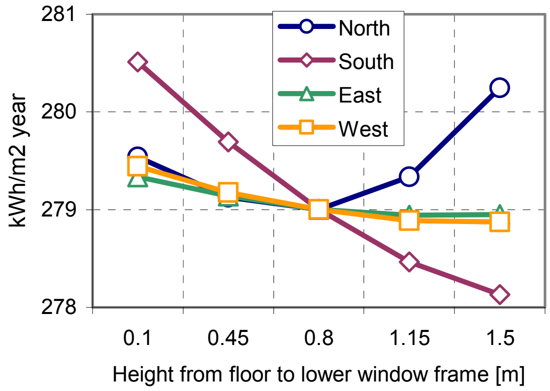

Figure 1

Yearly energy demand with different windows heights

We defined four different standard window glass types to choose from under the optimizing process. These different glass types range from high to low energy efficient and with a U-value range from 0.66 to 2.56 (see table 3). The energy effect of the different window types is shown in figure 2. The window type is the only varied parameter. To overcome some difficulties related to the EnergyPlus input format, we choose to give each window type a specific number and then set the step value to one.

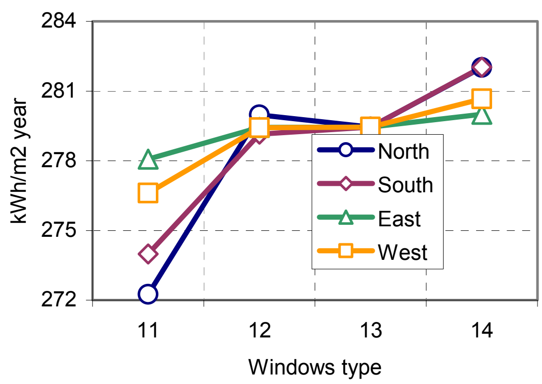

Figure 2

Yearly energy demand with different windows type

[5] COPYRIGHT BY NEMETSCHEK NORTH AMERICA INC.

[6] COPYRIGHT BY MICROSOFT INC.

The thermal mass of the building interior can have a positive effect on the comfort conditions and the heating and cooling power requirements as shown in figure 3. We defined three thermal mass steps to choose from under the optimizing process: heavy (0.15 m concrete), medium (0.12 m brick) and light (0.012 m plaster board wall with no insulation). Here we also had to overcome some difficulties related to the EnergyPlus input format, and had to give each thermal mass step a specific number and then set the step value to one.

A central feature of the Hook-Jeeves optimizing algorithm is that it reduces the step size if no further reduction in the objective function can be found for the current step size. Since the parameters related to both thermal mass and window type cannot use step-size reduction, we had to deviate from the formal definition of the Hook-Jeeves optimizing algorithm for these two design parameters. All the other design parameters use step size reduction.

The light internal thermal mass gave lowest annual energy consumption. This was an unexpected result, but it can be explained due to a lower average room temperature during the heating season.

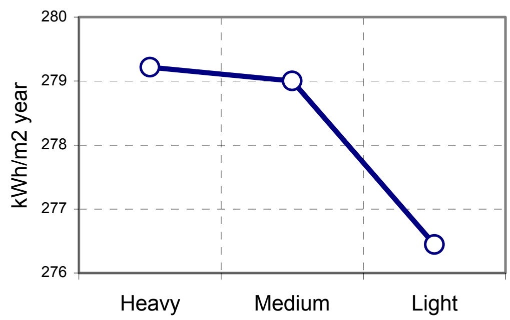

Figure 3
Yearly energy demand with different thermal mass

The start value of the exterior wall, floor and roof insulation thickness is the actual design value. The minimum value is the highest allowable U-value in the Norwegian Building Code and the maximum value is the assumed proper economic value.

The sun-, light- and thermal transmission factors of the shading device, are set to the same value in order not to complicate the optimizing process more than necessary. As shown in figure 4 the range is from 0.2 to 0.8 and with a start value of 0.5. The step value is set to 0.1.

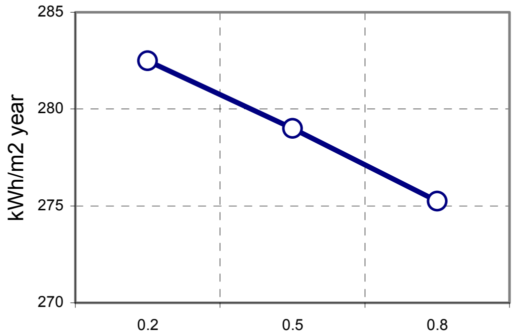

Figure 4
Yearly energy demand with different transmission factors

The night setback temperature has great influence on the buildings energy consumption as indicated in figure 5. Under the optimization process, this temperature can be varied within certain limits. If the night setback temperature is set to high, it will have a negative effect on energy conservation.

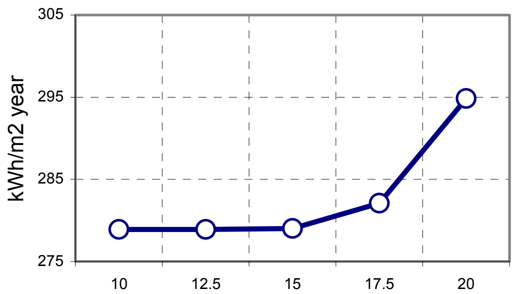

Figure 5
Yearly energy demand with different night-setback temperature

Given a set of design parameters, x, and an objective function (4), how much improvement can be achieved depends on the start values of the design parameters, x. The start values of the design parameters in this case study, correspond mostly to the energy design regulations in the Norwegian Building Code. Some of the start values used in the optimizing process are different from the actual design values. This has been done in order to achieve the best possible optimum value of the optimized design parameters.

RESULTS

Figures 6 and 7 shows the values at each iteration step. To achieve the minimum point a total of 122 EnergyPlus simulations were required. This took approx. 12 hours on a Pentium III computer (600 MHz and 256 MB ram) running Windows 2000. The optimization results in 22.5 % energy savings when compared to the actual design energy consumption.

Figure 7 shows that the total annual energy demand reduces from 222 kWh/m^2 (when start values are used) to an optimum of 168 kWh/m^2. Table 2 shows the parameter change that gives this reduction.

Table 1
Comparison of actual and optimal design

	Annual energy consumption (kWh/m^2)				PMV_avr
	E_tot	Q_heat	Q_cool	E_light	
Actual design	217	99.8	10.1	107.4	-0.2456
Optimal design	168	42.5	21.5	104.3	0.0162
Change (%)	-22.5	-57.4	+113	-3	

Compared with actual design (as built) the optimal design gives a 22.5 % annual energy reduction. This reduction is spread over the items shown in table 1.

If we look at the design values we see that it is mainly changes in window area, windows type and insulation thickness that contribute most to energy savings. The measures found by using optimization not only decrease operating costs, but also lead to better daylight usage and thermal comfort, which results in higher comfort for the building occupants.

CONCLUSION AND DISCUSSION

The case study shows that mathematical optimization can be a cost-effective tool that supports the designer in designing better buildings and HVAC system. The optimal design gave lower operating costs and higher comfort for the building occupants. Working trough the optimization process also gives the designer a better understanding of the building and the HVAC system behavior, and the complex interaction between the different design parameters.

Actual design will in most cases, differ from optimal design. This is mainly due to restrictions bound to a specific construction or special qualitative and quantitative factors that were not taken into consideration under construction of the mathematical model. To identify how actual design differs from optimal design we can introduce an Energy Efficiency Indicator of Design and Operation (EEIDO), defined by:

$$\eta = \frac{E\_tot_{Optimal\ design}}{E\_tot_{Actual\ design}} \quad (5)$$

where:

$E\_tot_{Optimal\ design}$ - Total energy consumption of optimal building design and operation;

$E\_tot_{Actual\ design}$ - Total energy consumption of actual building design and operation.

When using measured, total energy consumption and comparing this to optimal energy consumption the efficiency indicator can tell us how well the building is designed and operated. In the case study, the Energy Efficiency Indicator of Design and Operation (EEIDO) is 0.775.

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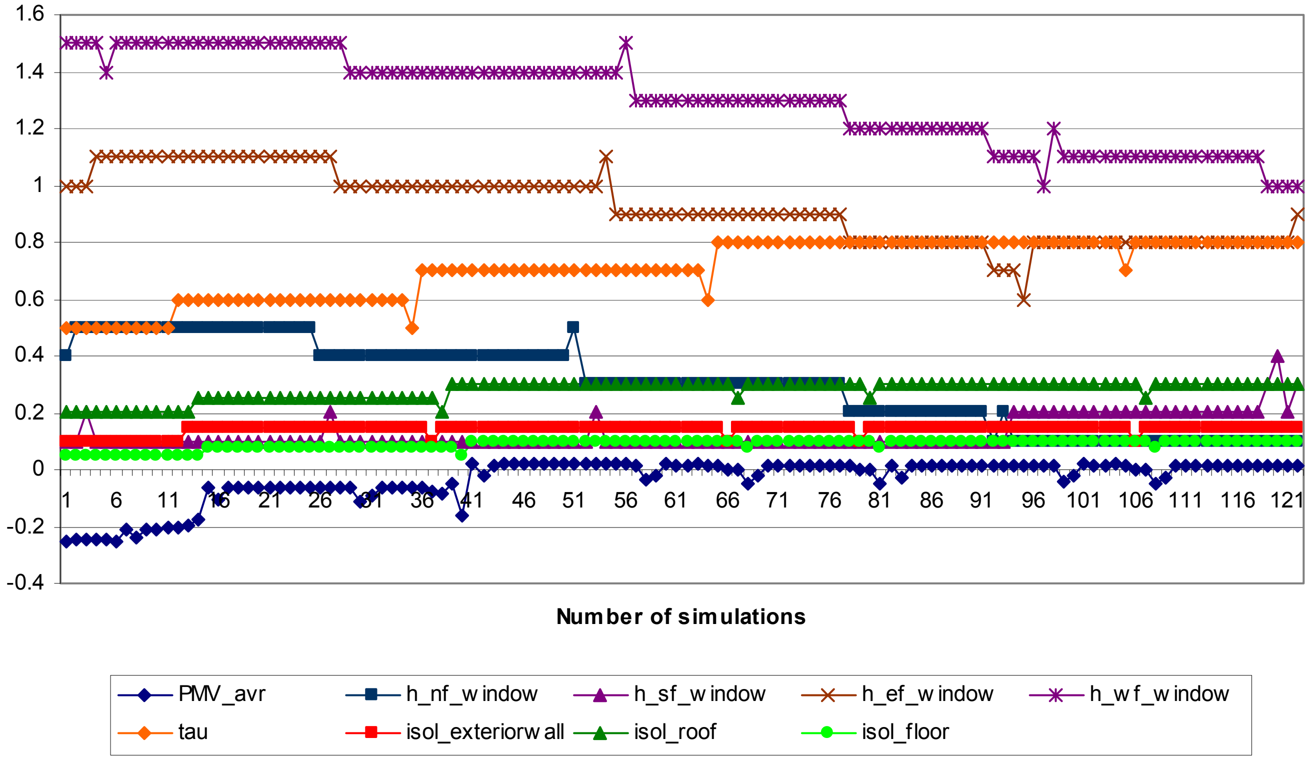

Figure 6
Variation of the design parameters (9 out of 14 shown). Several parameters are scaled to fit in the diagram. The Y-axis has therefore no unit (Trondheim).

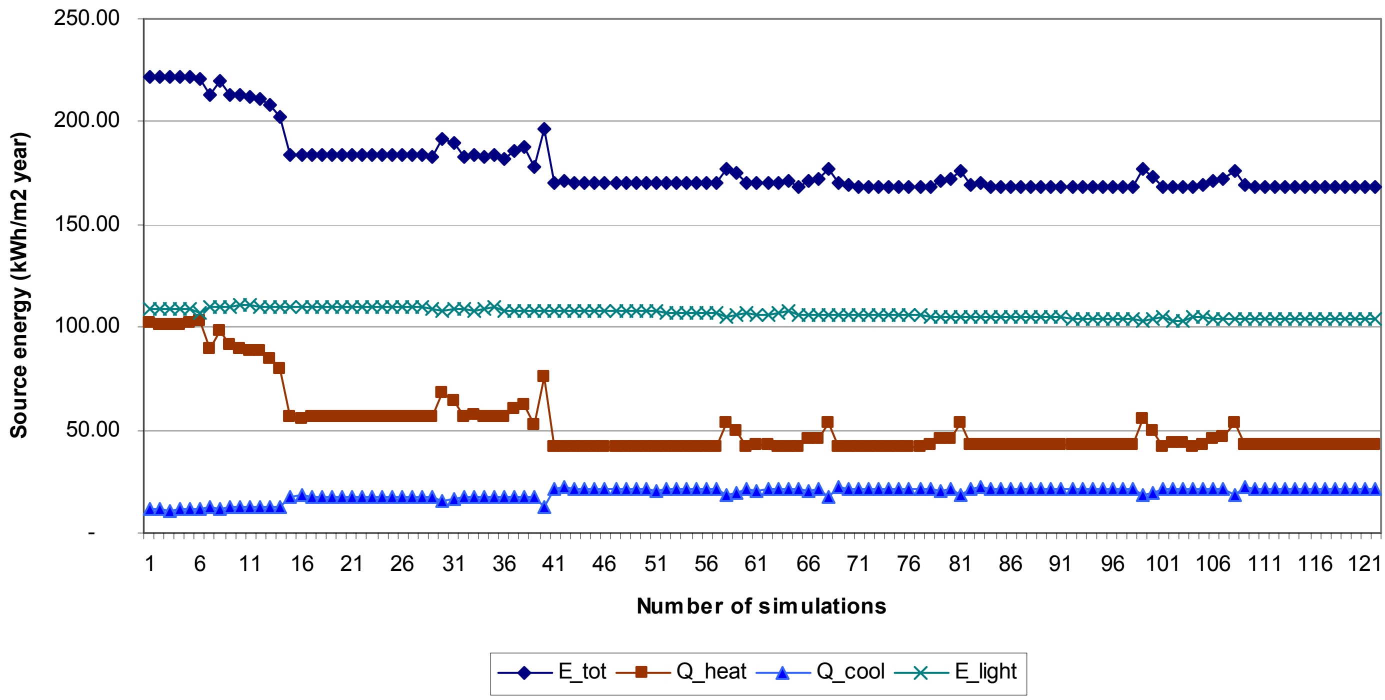

Figure 7
Results from the variation of the free parameters (Trondheim)

Table 2
Optimizing parameters

DESIGN PARAMETER	PARAMETER – NAME	DESCRIPTION	START VALUE	MIN. VALUE	MAX VALUE	STEP VALUE	OPTIMAL VALUE TRONDHEIM
Windows area	%h_nf_window%	Window – north façade; (m)	0.4	0.1	1.5	0.10	0.1
	%h_sf_window%	Window – south façade; (m)	0.1	0.1	1.5	0.10	0.3
	%h_ef_window%	Window – east façade; (m)	1.0	0.1	1.5	0.10	0.9
	%h_wf_window%	Window – east façade; (m)	1.5	0.1	1.5	0.10	1
Type of window	%nf_window%	Window – north façade	12	11	14	1	11
	%sf_window%	Window – south façade	11	11	14	1	11
	%ef_window%	Window – east façade	13	11	14	1	13
	%wf_window%	Window – east façade	14	11	14	1	13
Thermal mass	%term_mass%	Thermal mass	22	21	23	1	22
Ext. wall insul. Thick.	%isol_exteriorwall%	Mineral wool; (m)	0.10	0.05	0.15	0.05	0.15
Roof insul. Thickness	%isol_roof%	Mineral wool; (m)	0.20	0.10	0.30	0.10	0.3
Floor insul. Thickness	%isol_floor%	Foam insulation (Polystyrene), (m)	0.050	0.025	0.10	0.025	0.1
Shading dev. trans.	%tau%	Sun, light and thermal transmission	0.5	0.2	0.8	0.1	0.8
Night setback temp.	%night_temp%	Night setback temperature; (ºC)	15	10	20	1	12

Table 3
Windows type construction

ID	MATERIAL NAME	WINDOWS CONSTRUCTION	U-VALUE (W/m^2k)	SUN - TRANSMISSION	LIGHT - TRANSMISSION
11	Quadruple LoE Films (88) 3mm/8mm Krypton	CLEAR 3MM, KRYPTON 8MM, COATED POLY-88, KRYPTON 3MM, COATED POLY-88, KRYPTON 8MM, CLEAR 3MM;	0.66	0.34	0.62
12	Trp LoE (e2=e5=.1) Clr 3mm/6mm Air	LoE CLEAR 3MM, AIR 6MM, CLEAR 3MM, AIR 6MM, LoE CLEAR 3MM Rev	1.55	0.36	0.66
13	Trp LoE (e5=.1) Clr 3mm/6mm Air	CLEAR 3MM, AIR 6MM, CLEAR 3MM, AIR 6MM, LoE CLEAR 3MM Rev;	1.81	0.46	0.7
14	Dbl Clr 6mm/13mm Arg	CLEAR 6MM, ARGON 13MM, CLEAR 6MM;	2.56	0.6	0.78