Optimal Design of Building Envelopes

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ABSTRACT

A problem that often arises in building design is the determination of the design parameters related to the different aspects of the design (e.g., thermal performance characteristics, costs, indoor climate, aesthetics, etc.). A tool to assess the overall performance of the building is necessary to provide indicators for designers and contractors on the potential performance of a building or its retrofit. An important part of such a tool is its ability to perform optimization of buildings or parts thereof, taking into account their life-cycle cost and their life-cycle performance.

A method is developed that optimizes the building design based on life-cycle cost and indoor climate. Environmental impact and working environment are not included in the evaluation at this stage. The method is implemented in a tool that evaluates the building design within boundaries set up by the designer using a database containing information on different building components and systems. Life-cycle costs are based on net present value calculations.

INTRODUCTION

It is a well-known fact that the focus on the energy-related properties of building envelopes is important if the current energy consumption in buildings is to be lowered. However, it is also obvious that energy savings in buildings can be obtained in many ways. Therefore, it is important to base the design of the building envelope on an optimization of the different performance aspects (e.g., the insulation level). The designer needs a methodology for optimization to determine the level of energy savings versus extra investment costs of the building envelope or determination of other aspects of the building envelope. Integration of more aspects, including indoor climate and service life of the components, only increases the need for such a methodology.

Generally, many aspects characterize a building envelope. Some of these are governed by building regulations, etc., and others can be almost freely varied inside a certain span. These are termed *nonoptimizable aspects* and *optimizable aspects*, respectively. Nonoptimizable aspects may be structural properties and fire safety-related properties, whereas energy performance is an optimizable aspect as it may be varied by change of the design. Such change influences the cost of investment and operation, requiring a methodology to determine the proper level of thermal performance and other optimizable aspects.

PERFORMANCE REQUIREMENTS AND CHARACTERIZATION

Building activities mostly start with the expression of the customer's need and end with the customer's use of the building. Building activities can normally be divided into the following phases (Hendriks and Hens 2000):

1. Customer's signaling of need
2. Identification and description of requirements
3. Functional requirements translation, product specification, and performance optimization
4. Construction/retrofitting of the building
5. Assessment of performance

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6. Transfer of building to customer; management and maintenance
7. Building use

Some of these phases may be difficult to complete. Examples are the translation of the customer's requirements to product specification and the process of performance optimization. Translation of the customer's requirements are needed, as the term "adequate indoor climate to facilitate office work during entire year" cannot easily be matched against the properties of, e.g., a window or an exterior wall, as these are described by their thermal performance. To aid the translation of the customer's requirements into product specification, Hendriks and Hens (2000) compiled a list containing a substantial amount of design considerations ranging from thermal comfort, through anti-burglar security, to space requirements for the building with links being made between the design considerations and the relevant building physics-related properties.

Determining the building physics-related properties may be a very time-consuming activity, as this includes obtaining properties related to heat transfer (both one- and multidimensional heat flow), static, and acoustics, etc., as well as information on pricing and durability. To avoid repetition of the gathering and processing of data, all relevant information should be stored in a building component database. Once entered, the data are readily available for different applications, being tools for calculations of the overall heat loss for buildings or, as in this instance, tools for optimization of the building envelope. An example on a format for characterizing building envelope components has been given by Rudbeck et al. (2000). Once the information is gathered and stored in a database, calculation of the performance of different combinations of envelope components or variants thereof can be made, being one of the inputs for the optimization that is to follow. Rose and Svendsen (1999) show the development of a database that is linked to an energy-related building simulation program.

Once the demands of the customer have been formulated and translated into building physics-related terms, the matching between demand and supply is initiated. Most likely, it is impossible to fulfill all demands of the customer, especially if the demand is a low-cost high-quality building. If only some of the customer's demand may be met, a priority of the demands is needed. Generally, the demands of the customer are separated into two parts—those demands that must be fulfilled and those demands where the level is not yet decided. The demands that must be fulfilled (e.g., fire safety or indoor climate) should be addressed first. Once these aspects have been decided, the matching process continues with the remaining aspects. The remaining aspects include thermal insulation thickness, cost of building and operation, maintenance-related properties, etc. The levels of these are not necessarily governed by building regulations and it is therefore possible to choose from several different components or several different variants of a component. As the number of possible building designs may still be counted in thousands or millions, the designer should have the possibility of reducing the number of possible designs and thereby provide the customer with the best solution. To find the best solution among the many possibilities, an optimization routine should be considered, as an optimization routine is a prerequisite for further work.

OPTIMIZATION BASED ON ECONOMIC CALCULATIONS

A parameter with much focus during design and construction of buildings is the cost associated with these two processes. In a traditional evaluation of the costs, focus is mainly on the investment costs, with only little regard to future costs. Initiatives that reduce the future costs (e.g., energy savings, durable building designs) often result in larger investment costs (e.g., because of addition of thermal insulation, changes in the design, more durable building materials, etc.). If future costs are not included in the evaluation, these initiatives will not be implemented. Therefore, the cost of different building designs should be evaluated based on calculation of life-cycle costs (LCC), which include investment costs, maintenance costs, energy costs, service life of building components and systems, and scrap value. As the impact of costs may change through time due to inflation and interest rates, these aspects should also be taken into account. Finally, an estimation of the service life of the different building designs is needed to evaluate costs for maintenance and replacement.

Methods used to combine the effects of all these aspects once they are found already exist and are generally referred to as life-cycle-cost (LCC) calculation methods. A description of the LCC-method may be found in ASTM (1994). In the LCC-method, the net present value (NPV) is used to integrate the different aspects of costs (investment, operation, maintenance, scrap value, etc.). The basis of an NPV calculation is that all current and future costs are discounted to the present. By this approach, it becomes possible to compare the economical performance of several alternatives even though the distribution of associated costs through time may be different.

Using the traditional LCC and NPV calculation makes it possible to optimize relatively simple envelopes or components (i.e., it is possible to see the economic impact of changing the insulation thickness in an exterior wall and thereby finding the optimal insulation thickness or to decide which of a number of components to use based on an evaluation of the NPV of the LCC). However, once several aspects in a building design are to be changed simultaneously, these simple general methods fail. Instead, an automated optimization process is needed.

OPTIMIZATION OF BUILDING DESIGN

The influence of a single design parameter on the overall building performance is very difficult to evaluate, as the overall building performance is the result of the interaction between the different design parameters. Therefore, optimiza-

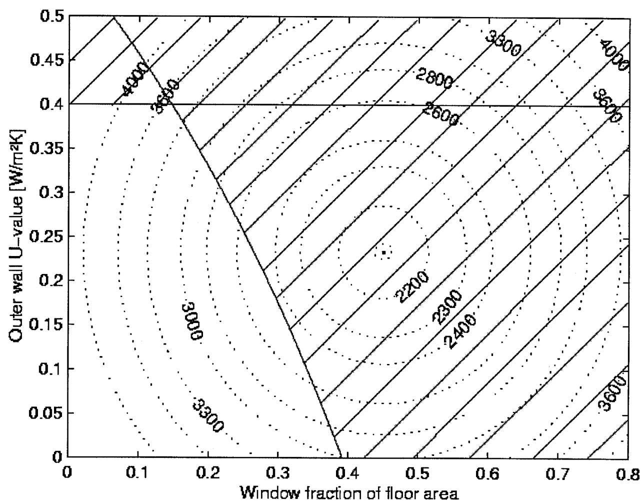

Figure 1 *Optimization problem in the case of two design parameters constrained by the building code. The contour lines show the life-cycle cost. The minimal life-cycle cost is found with an outer-wall U-factor of 0.23 W/m²K (0.041 Btu/ft²·h·°F) and a window fraction of 0.45. The building code states a maximum U-factor of the outer wall and a maximal acceptable heat loss. The bounds of these constraints are shown as solid lines and, to meet the constraints, the solution must not reside in the hatched area (1 W/m²K = 0.1761 Btu/ft²·h·°F).*

tion of building design cannot be done by optimizing the different design parameters individually. In addition, the building design may be constrained by wishes of the customer, building codes, and standards. Constraints often found in building codes and standards are limitations on the energy use for heating and ventilation and criteria concerning the indoor environment. Optimization must therefore be performed, taking into account the overall performance of the building, and the design meeting the constraints given by the customer, building codes, and standards must be reached at the lowest life-cycle cost. Recent studies show the possibilities of applying optimization with many design parameters to building retrofits (Gustafsson 1998) and design of low energy buildings (Peippo et al. 1999).

Figure 1 illustrates the optimization problem in the situation where heat loss is constrained by the building code. The variable design parameters are the outer wall U-factor and the window fraction of the floor area. The building code states a maximum U-factor of the outer wall and a maximal acceptable heat loss. The bounds of these constraints are shown as solid lines and, to meet the constraints, the solution must not reside in the hatched area. The contour lines show the life-cycle cost. The minimal life-cycle cost is found with an outer wall U-factor of 0.23 W/m²K (0.041 Btu/ft²·h·°F) and a window fraction of 0.45. The building design with the lowest life-cycle cost has an energy demand that exceeds the given constraints and is therefore not valid. Since the constraint exists, the optimal solution has to respect this, and the optimal design is found on the bound of the hatched area and results in a higher life-cycle cost. This example illustrates the general constrained optimization problem in two dimensions.

In a real design process, many design parameters must be considered and a number of different constraints may exist. This necessitates the use of an efficient optimization algorithm.

Life-cycle cost, energy demand, and other values used in the optimization are not linear functions of the design parameters. This gives a nonlinear optimization problem with nonlinear constraints. Many different approaches to solve optimization problems exist (e.g., Wetter 2000). The different approaches have different efficiencies and none of them guarantees that a global optimum is found. Even though a global optimum is not obtained, optimization still results in cost-effective improvement of the overall performance of buildings.

To aid the building designer in the early design process, a building design optimization tool is being developed. In the early design process, the building designer formulates some preliminary design ideas based on translation of the functional requirements. These preliminary ideas are used as input in the optimization process. The design tool uses a database containing information such as thermal properties, cost and service life for different existing building components and systems, and variants thereof. From this database, the designer chooses the building parts and systems to consider in the optimization. The design parameters used to describe the building are listed in Table 1. Many of the design parameters are discrete and are described by integer values where the integer values represent different building components or systems taken from the database. Different building designs are obtained by combining the building components and systems in the database. The building design is also described by some geometric parameters. The window area can be varied as a fraction of the floor area. The building can be rotated to evaluate the best orientation, and the aspect ratio given by the length of the building divided by the width can be varied.

The building design optimization tool uses an existing optimization algorithm developed for global optimization (Holmström et al. 1999). The optimization algorithm has no criterion detecting convergence. Therefore, it runs for a predefined number of function evaluations. Some experiments must be performed to estimate the number of function evaluations necessary to reach the global optimum.

Life-cycle cost, energy demand, and indoor environment are calculated based on the design parameters. The thermal performance is evaluated using a simple dynamic thermal model of the building with one node representing the thermal mass of the zone. The temperature of the indoor air is calculated on an hourly basis from hourly values of outdoor temper-

TABLE 1
Design Parameters*

Design parameter	Type
Outer wall construction	I
Deck construction	I
Ceiling construction	I
Inner wall construction	I
Window construction	I
Window fraction	F
Heating system	I
Cooling system	I
Ventilation system	I
Solar domestic hot water system	I
Solar area	F
Orientation	F
Aspect ratio	F
Shading device	I
Number of stories	I

* Note: Design parameters of type I can only be integer values and are used to choose between different building components and systems in the database within the given limits. Design parameters of type F can be varied freely within the given lower limits.

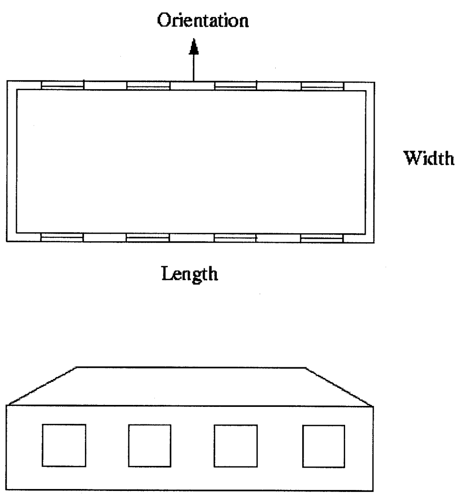

Figure 2 *Sketch showing the ground plan and facade of a building.*

ature, solar gains through windows, and internal heat gains from occupants and equipment.

As an example, optimization is performed on a one-story residential building. A sketch of the building is shown in Figure 2 and data used in the optimization are given in Table 2. The building has eight equally sized rooms, each with a window. The energy demand for heating and ventilation must

TABLE 2
Data Describing Building, Calculation Time, Real Interest Rate, and Energy Prices*

Floor area	100 m^2 (1076 ft^2)
Air change rate	0.5 h^{-1}
Infiltration	0.1 h^{-1}
Heating setpoint	20^{o}C (68^{o}F)
Internal load	5 W/m^2 (1.58 Btu/h·ft)
Calculation time	30 years
Real interest rate	2%
Electricity price	1.5 DKK/kWh
Heating energy price (District heating/Oil/Gas)	0.3/0.8/0.8 DKK/kWh

* Note: 1 DKK is approximately 13 cents.

be below 250 MJ/m^2 (236,950 Btu), as stated in the building code (*Building Regulations* 1995), and to ensure a reasonable thermal indoor environment, the indoor air temperature may not exceed 26^{o}C (79^{o}F) more than 100 hours per year as proposed in DS474 (1993). The building components and systems are taken from the building component database, which describes the thermal properties, costs, service life, efficiency of HVAC components, etc., of different building components and systems and variations thereof. Not all design parameters in Table 1 are used in this example. The design parameters considered in this example and their upper and lower limits are given in Table 3. The outer wall, ceiling, and floor are described by the insulation thickness, and the window is described by the thermal transmittance and total solar energy transmittance of the glazing. The orientation of the windows follows the orientation of the building.

The optimized solution is shown in Table 3. The energy demand for heating and ventilation is 247.5 MJ/m^2 (21,787 Btu/ft^2) and indoor air temperature is above 26°C (79°F) for 100 hours, which are within the limits. In the optimization, the chosen heating system is district heating. The energy price for district heating is low. Therefore, extra insulation and mechanical ventilation with heat recovery that results in an energy demand well below the limit in the building code are not cost-effective. Different design possibilities can be investigated using other limits for the optimization, and parametric studies can be performed based on the optimized solution. The building designer should critically use the optimized solution as a guideline for further investigations. The impact of small design changes on the LCC can be estimated by evaluating the flatness of the response surface around the optimal point. This will allow the designer to determine the amount of flexibility one has to have to meet other soft constraints without significant impact on the LCC.

TABLE 3
Limits and Results

Parameter	Options	Solution
Outer wall	Insulation: 125 to 400 mm (4.9-15.7 in.)	125 mm (4.9 in.)
Deck	Insulation: 70 to 300 mm (2.8-11.8 in.)	70 mm (2.8 in.)
Ceiling	Insulation: 250 to 600 mm (9.8-23.6 in.)	250mm (9.8 in.)
Inner wall	Light, medium heavy, heavy	Light
Window*	U = 2.9 W/m^{2}K (0.51 Btu/ft^2·h·^{o}F); g = 0.76 U = 1 W/m^{2}K (0.18 Btu/ft^2·h·^{o}F); g = 0.59	U = 1 W/m^{2}K (0.18 Btu/ft^2·h·^{o}F) g = 0.59
Window fraction	0.1 to 0.5	0.10
Heating system	Gas, oil, or district heating	District heating
Ventilation	Natural ventilation or mechanical ventilation with heat recovery	Natural ventilation
Orientation	0^o to 180^o	10^o
Aspect ratio	1 to 5	1.35
Energy demand	Max. 250 MJ/m^2 (22,007 Btu/ft^2)	247.5 MJ/m^2 (21,787 Btu/ft^2)
Hours above 26^{o}C	Max. 100 hours	100

* The values in the table are the values for the glazing. U is the thermal transmittance and g is the total solar energy transmittance.

After a number of trial-and-error runs, a number of 10,000 function evaluations is found to give a solution reasonably near to the global optimum. Therefore, the optimization has been performed using 10,000 function evaluations. This used approximately 21 CPU hours on a standard 500 MHz computer. The number of function evaluations does not guarantee that the optimal solution is reached. Especially the design parameters not represented by integer values may not have reached their optimal values. To improve the result, more function evaluations can be performed or the limits on the design parameters can be tightened.

The optimization is based on the life-cycle cost calculations for a period based on investment costs, maintenance costs, and service life of building components and systems and the real interest rate. The real interest rate and energy prices may change during the period, and investment costs, maintenance costs, and service life of building components and systems are not easily obtained. Especially the maintenance cost and service life are not well documented. Different methods have been proposed to determine service life (ISO 1998; Moser 1999) and maintenance costs (Rudbeck 1999) but lack empirical data to be validated.

CONCLUSIONS

In this paper, a tool to assess the overall performance of a building is presented. The tool is to be used by both designers and contractors to assess the performance of buildings and to choose between different building designs. Performance assessment of buildings is performed using a methodology, taking into account all relevant aspects of the construction (e.g., user comfort, energy performance, costs, etc.). The performance aspects are matched against building requirements and possible designs are chosen from the ones that meet the performance requirements. By applying the methodology on an example, the usability of the methodology is shown.

Once the possible designs are found, optimization of the building designs takes place. A layout of an optimization method for whole buildings is proposed. Although the method is a step forward compared to traditional methods, where only components can be optimized, the methods still need development. Also, the reliability of pricing information for the calculations needs improvement.

Once the method is fully developed, it can be used to optimize whole buildings as far as possible. As it will then be possible to include the future cost of the building into the optimization, the most likely outcome of the use of the method is probably that the building designs will be more prepared for the future (i.e., that the focus of the future building design will be on optimization of the overall building performance and not only on minimization of the investment cost, which was one of the main priorities of the past).

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